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# Introductory Review of Impairments in Optical OFDM Systems

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## ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) is a special form of Multi-Carrier modulation technique, is widely used in both wireless communications and cable-based data transmission. OFDM has been extensively studied in the Radio Frequency (RF) domain and recent research focuses on applying OFDM technology in optical fiber communication systems referred to as Optical OFDM (OOFDM). Optical OFDM is well suited for high-speed transmission systems providing high spectral efficiency. The growing interest in OOFDM systems due to an increase in data rates has fostered the appearance of a large variety of solutions for different applications. The OFDM technique is highly desirable for flexible and energy-efficient optical BackBone (BB) and Back Haul (BH) systems. It is also proposed as a future proof technique for the implementation of flexible resource allocation in Cognitive Optical Networks (CON). Fiber impairment assessment and adaptive compensation become critical in energy-efficient transport and CON implementations. The performance of practical fiber links in BB and BH networks is not only degraded by dispersion but also due to various nonlinear effects and noises. The large Peak to Average Power Ratio (PAPR) in OOFDM systems further exacerbates the fiber nonlinear effects such as Self Phase Modulation (SPM), Cross Phase Modulation (XPM), and Four-Wave Mixing (FWM). Application of suitable impairment mitigation involves the accurate assessment of the impact of the impairment, particularly in flexible resource allocation scenarios. The existing analytical models for OOFDM systems consider the only partial impact of fiber impairments.

Keywords: OOFDM, Impairments

## 1. Introduction

A Cognitive Optical Network (CON) is a new paradigm to address the increasing complexity of optical networks and provide an efficient autonomic as well as user-controlled network. The basic concept is to make the network more intelligent in order to dynamically adapt to current network conditions and to make decisions based on past learning. The cognitive optical network plans and takes decisions based on the information collected from the network and the target Quality of Service requirements of the users. Orthogonal Frequency Division Multiplexing (OFDM) is a special form of Multicarrier (MC) modulation that is widely used in both wireless communications and cable-based data transmission. OFDM has been extensively studied in the Radio Frequency (RF) domain and recent research focuses on applying OFDM technology in optical fiber communications referred to as Optical OFDM (OOFDM). Optical OFDM is well suited for high-speed transmission systems harnessing high spectral efficiency. The growing interest in OOFDM is because of the demand for high data rates owing to a growing variety of applications.

OFDM is highly desirable for designing flexible and energy-efficient optical BackBone (BB) and Back Haul (BH) systems. It is also viewed as a future proof technique for the implementation of flexible resource allocation within Cognitive Optical Networks. Fiber impairment assessment and adaptive compensation become critical in CON implementations. If the OFDM signal is transmitted through optical fiber links, linear and nonlinear impairments cause a cascading effect increasing the distortion and resulting in Bit Error Rate (BER) degradation. Hence, the usage of OFDM in CONs necessitates the accurate assessment of fiber impairments and its adaptive compensation.

The performance of practical fiber links in BB and BH networks is not only degraded by dispersion but also due to various nonlinear effects and noises. Existing analytical models in OOFDM systems consider only the partial impact of fiber impairments. Hence, the proposed research work aims to develop a comprehensive analytical model, which includes the combined impact of laser phase fluctuations, fiber dispersion, Self-Phase Modulation (SPM), Cross Phase Modulation (XPM), Four-Wave Mixing (FWM), the nonlinear phase noise due to the interaction of Amplified Spontaneous Emission (ASE) with fiber nonlinearities and photodetector noises. To improve the overall performance of the fiber optic system, the proposed analytical model assesses various impairments and the required adaptive compensation. The proposed system implements a linear and nonlinear Peak-to-Average Power Ratio (PAPR) reduction technique for fiber nonlinearity mitigation in OFDM-based dispersion managed links. Further, the proposed research uses Few Mode Fiber

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(FMF) whenever necessary to increase the nonlinearity threshold in comparison to that of a Standard Single-Mode Fiber (SSMF).Here introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 9.5 pt. Here follows further instructions for authors.

## 2. Cognitive Optical Networks

A cognitive network is a network with a cognitive process that can perceive current network conditions and then plan, decide and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all the while taking into account end-to-end goals.

The Cognitive Optical Network (CON) is promising to be the major step towards an efficient autonomic as well as user-controlled network to address the increasing complexity of optical networks. Cognitive optical networks aim to introduce cognition on multiple planes (e.g. data plane, control plane, management plane, service plane, application layer) in order to perceive current network conditions. The ultimate goal of CON is first to enhance the optical network infrastructure by providing cognition on devices, systems, and layers. In a cognitive optical network, the environment is never static. The protocols, mechanisms, algorithms, devices, and systems are constantly learning and adapting to environmental conditions for delivering the best possible performance.

Cognitive optical networks consist of hardware/software modules that are able to self adapt, self configure and self optimize their structure and behavior. Modulation format, bit rate, number of wavelengths used, launch power, amplification gain, compensation, and many others can be adapted, repurposed, and optimized according to the needs of the service provider governed by the user and application requirements. A self-optimized physical layer can also observe local and network-wide physical impairments to optimize the performance of individual devices and nodes to guarantee end-to-end Quality of Transmission (QoT) levels. For these reasons hardware programmable elements have to be deployed such that the state-of-the-art optical modules can be controlled and in turn, converted to cognitive-enabled systems.

## 3. Optical Fiber Communication

Optical fiber communication is now an established technology and owes the popularity to its many advantages such as high bandwidth (around 10s of THz), low loss (around 0.2 dB/km), and freedom from electromagnetic interference (Agarwal 2002). The demand for bandwidth is increasing exponentially at about 60% every year, and hence the extent of research and technology development has become exceedingly important. Fiber-optic communication has progressed through several distinct generations. The first generation operated near 0.8 µm and became commercially available in 1980 (Agarwal 2002). The bit rate was 45 Mb/s and repeater spacing was up to 10 km. The second generation became available in 1988. 1.3 µm wavelengths was used due to less fiber loss (<1 dB/km) and the limitation of the system came from pulse broadening caused by intermodal dispersion leading to Inter Symbol Interference (ISI).

To reduce the dispersion effect, Single-Mode Fiber (SMF) was introduced. Compared to Multi-Mode Fiber (MMF), SMF is designed to support only one mode and suffers less from pulse broadening. The attenuation of silica fiber becomes minimum near 1.55µm (0.2 dB/km). Therefore, to take advantage of minimum loss, third-generation systems operated at 1.55 µm. To minimize dispersion, Dispersion Shifted Fiber (DSF) was used with low dispersion resulting in 10 Gb/s and repeater spacing of up to 100 km. Also, in this generation, coherent fiber optic systems were studied extensively (Kikuchi 2010). Coherent detection offers higher sensitivity but coherent receiver design is more complex. The fourth-generation optical system introduced optical amplifiers and Wavelength Division Multiplexing (WDM) systems which made submarine transmission systems feasible for intercontinental communication. The fifth generation of fiber communication systems is concerned with extending the wavelength range over which a WDM system can operate simultaneously. This generation of systems increased the data rate of each channel within the WDM multiplex by improving spectral efficiency.

The current generation of optical communication systems has reached a fundamental limit to the capacity of ~ 100 Tb/s for conventional Single-Mode Fiber (SMF) based systems (Toshio et al. 2012). This limit arises from the interplay of a number of factors including the Shannon limit, optical fiber nonlinearities, the fiber fusing effect, as well as optical amplifier bandwidth. In order to overcome these limitations and achieve far higher transmission capacities, Space Division Multiplexing (SDM) can be implemented by establishing independent diverse light paths in a single fiber. This can be achieved in two ways. The first is via Multi-Core Fibers (MCFs), where multiple cores are incorporated in a single strand of glass, which provides a proportional increase in the number of spatial dimensions. The second way to introduce diverse light paths is based on Multi-Mode Fibers (MMFs), where a single strand of fiber has one core with a sufficiently large cross-section area to support a number of independent guiding modes. The modes can then be exploited as independent channels, which are referred to as Mode Division Multiplexing (MDM).

## 4. OFDM Systems

Modulation schemes are broadly classified as, Single Carrier (SC) and Multi-Carrier (MC). The choice of modulation scheme aims at maximizing spectral efficiency in the same available bandwidth (David Tse & Pramod 2007). SC system capacity is limited due to Inter Symbol Interference (ISI) and the primary motivation for transmitting the data on multiple carriers is to reduce the ISI and thus, eliminate the performance degradation that is incurred in the SC system. Frequency Division Multiplexing (FDM) extends the concept of SC modulation by dividing the available spectrum into many carriers, each being modulated by a low data rate stream. Since, each subcarrier has a lower information rate, the data symbol periods in a digital system will be longer, adding some additional immunity to impulse noise and reflections. Advantages of MC include using separate modulation/demodulation customized to a particular type of data or sending out banks of dissimilar data that can be best sent using multiple and possibly different modulation schemes.

In SC systems, fading or interference can cause the entire link to fail. In MC systems, however, only a small number of subcarriers may be affected. The task of complex receiver equalization is significantly simplified in MC systems (Proakis 1995). FDM systems usually require a guard band between modulated subcarriers to prevent the spectrum of one subcarrier from interfering with another. These guard bands lower the system's effective information rate when compared to a SC system. Major limitations of FDM include (i) difficulty in synchronizing the carriers and (ii) the requirement of strict linear amplification (Cripps 1999).

Orthogonal Frequency Division Multiplexing (OFDM) is a form of multicarrier modulation being widely used in both wired and wireless communications (Hee & Hong 2005). Two competitive Fourth generation (4G) mobile network standards, Worldwide Interoperability for Microwave Access (WiMAX, or IEEE 802.16) and Long Term Evolution (LTE), have both adopted OFDM as the core of their physical layer. The major strengths of OFDM are efficient bandwidth utilization, minimum ISI, robustness over frequency selective fading channels and to burst error.

With the advancement of powerful silicon Digital Signal Processing (DSP) technology, OFDM has seen wide deployment in a broad range of applications. These include cable-based data transmission technique Discrete Multitone (DMT); Digital broadcasting services like the Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB) proposed by Reimers (1998); Wireless ATM networks; Asymmetric Digital Subscriber Loop (ADSL) (Saltzberg1998); High Definition Television (HDTV); Highbit-rate Digital Subscriber Lines (HDSL); Very High-speed Digital Subscriber Lines (VHDSL); LTE-Advanced and Wi-Fi. OFDM has also been recently applied for optical communications.

## 5. Optical OFDM Systems

OFDM has been extensively studied in the Radio Frequency (RF) domain and recent research has focused on applying OFDM within optical fiber communication systems referred to as Optical OFDM (OOFDM). In RF OFDM, the signal is transmitted in free space; therefore it is not subject to nonlinearities. But in OOFDM, the fiber channel is nonlinear coupled with fiber dispersion. So, the optical channel is more demanding than the wireless channel. The growing interest for OOFDM is due to an increase in the demand for higher data rates owing to a large variety of applications. Optical OFDM is a promising transmission format mainly due to its high spectral efficiency and inherent dynamic bandwidth capabilities. Figure 1.1 shows the transmitter architectures for single carrier and multicarrier optical systems. Single carrier systems employ a relatively simple architecture, in which discrete digital level modulation is fed into the two arms of the Quadrature Phase Shift Keying (QPSK) modulator. In contrast, the OFDM comprises electronic Digital Signal Processing (DSP) module and a Digital to Analog Converter (DAC) which are required for complex OFDM signal generation at the transmit end.

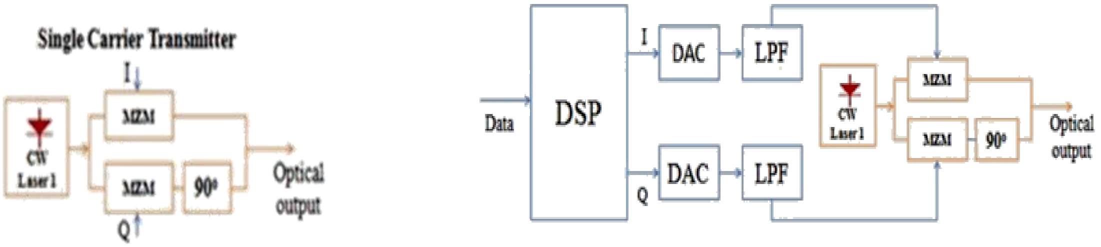

**Fig. 1: Transmitter architecture (a) Single Carries Systems, (b) Multicarrier systems**

The OFDM transmitter strictly enforces linearity in each component. In SC systems, the information is coded in the time domain, whereas in OFDM, the information is encoded in the frequency domain, more precisely onto each individual subcarrier.

## 6. Peak To Average Power Ratio In OFDM

OFDM suffers from two fundamental problems: (i) Frequency offset and phase noise (ii) Large Peak to Average Power Ratio (PAPR). Frequency offset and phase noise occurs because of the relatively long symbol length compared to that of the single carrier. Frequency offset and phase noise lead to Inter-Carrier Interference (ICI). However, these disadvantages obviously have not prevented OFDM from gaining popularity in both RF and optical communications. A high PAPR has been cited as one of the major drawbacks of the OFDM modulation format. PAPR is a random variable because it is a function of input data, which is also a random variable. Therefore, PAPR can be calculated from determining the average number of times that the envelope of a signal crosses a given level. PAPR is defined as in Equation (1):

$$PAPR = \frac{max_{\ t\in[0,T]}|x(t)|^2}{E\{|x(t)|^2\}} \qquad (1)$$

where E{.} is the expected value operator. The amplitude of a multicarrier signal follows the Rayleigh distribution. In general, most of the signals operate in the discrete-time domain. Therefore to approximate true PAPR values, it becomes necessary to oversample the continuous signal x(t) by an over sampling factor of Los, where Los is an integer larger than or equal to one. The Los-time oversampled signal xk is given in Equation (2):

$$x_k = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} X_n \emptyset_n\,(k) \qquad (2)$$

where $\boldsymbol{\emptyset_n(k) = e^{j2\pi nk/L_{os}N};}$ for k=0,1,…,$L_{os}$N-1.

PAPR computed from the Los-times oversampled time domain signal samples is given in Equation (3) as:

$$PAPR = \frac{max\ [|x_k|^2]}{E[|x_k|^2]} \qquad (3)$$

where E[|xk|2] denotes the average value over the time duration of OFDM symbol.

The Complementary Cumulative Distribution Function (CCDF) is one of the most frequently used performance measures for PAPR. CCDF of the PAPR denotes the probability that the PAPR of a data block exceeds a given threshold z. The Cumulative Distribution Function (CDF) of the amplitude of a signal sample is given by Equation (4):

$$F\ (z)\ = 1 - \ exp(z) \qquad (4)$$

The CCDF of the PAPR of a data block with Nyquist sampling rate is derived as in Equation (5):

$$\begin{aligned} P\ (PAPR > z)\ &= 1 - \ P\ (PAPR <= z) \\ &= \ 1 - F\ (z\ )N = 1 - (1 - exp(-z))N \qquad (5) \end{aligned}$$

Equation (5) assumes that the N time domain signal samples are mutually independent and uncorrelated (Wunder & Boche 2003).

In optical OFDM (OOFDM) systems, peak power increases the fiber nonlinear effects such as Self Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four Wave Mixing (FWM) (Agarwal 2001). By applying suitable PAPR reduction schemes, peak power of the OOFDM signal can be reduced, which results in reduction of fiber nonlinear effects (Brian Krongold et al. 2008 & Weilin Li et al. 2009).

## 7. Impairments in Optical OFDM Systems

Impairments in OOFDM can be broadly classified into three categories as shown in Figure 2. These noises, linear and nonlinear phenomena exist along the fiber link and influence each other. The interaction between these phenomena may lead to deterministic as well as stochastic impairments. A brief discussion on the fiber impairments is presented in the following sections.

In the case of OFDM signal transmission over fiber optic links, the fiber impairments cause a gradual walk-off between the main optical carrier and the OFDM subcarriers as the fiber length increases. This is illustrated in Figure 1.3. In addition, Phase Noise (PN) will affect the phase factor of each received baseband OFDM symbol.

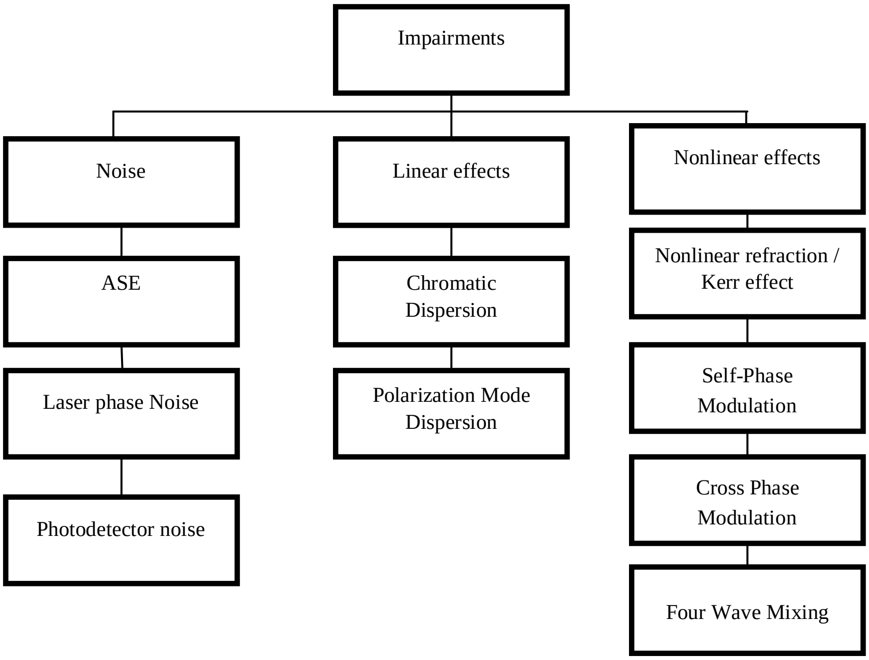

**Fig. 2: Impairments in Optical OFDM systems.**

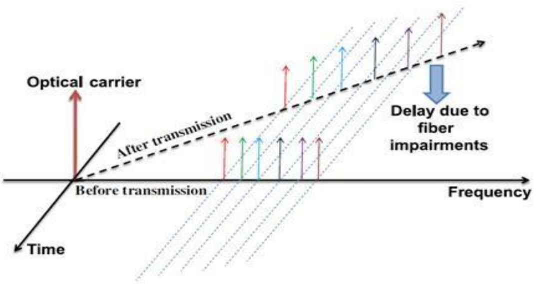

**Fig. 3 Impact of fiber impairments in OFDM systems.**

### 7.1 Noise

Optical transmission systems suffer from loss as signals propagate through the fiber. Despite the low fiber loss of about 0.2 dB/km around the 1550 nm wavelength range, the signal quality of long haul systems is impacted. To ensure an acceptable Signal-to-Noise Ratio (SNR), the required number Erbium-Doped Fiber Amplifiers (EDFA) need to be introduced in the fiber link. Amplified Spontaneous Emission (ASE) noise arises from EDFA due to the spontaneous emission of photons and it can be modelled as an Additive White Gaussian Noise (AWGN). The impact of ASE becomes more serious when its interact with Kerr nonlinearities. For a multi-span fiber optic link, the noise spectral density per state of polarization is given by Equation (6):

$$\rho_{ASE} = (G-1)hfn_{sp}\,(6)$$

where G is the amplifier gain, h is Planck’s constant, f is the carrier frequency and nsp is spontaneous noise factor. There are also other sources of noise such as laser phase noise of the transmitter, the shot noise and thermal noise of the receiver that impact on system performance. But in case of multi-span fiber optic systems the impact is relatively lower than that of ASE noise.

### 7.2 Linear Effects

In a general fiber transmission system, information is modulated and sent as a series of light pulses representing binary encoded data. As the pulses travel through the fiber, they start spreading, losing their original shape and hence overlap with neighbouring pulses and subsequently becoming indistinguishable at the receiver. Dispersion is the general term applied to this effect and the impact is ISI. Linear effects in the popularly used SMFs are classified into Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD).

Chromatic dispersion is a phenomenon which is created because of dependence of group index on wavelength which causes a temporal broadening of optical pulses as they propagate through the fiber (Agarwal 2001). It has two major components in standard single mode fibers: Waveguide and Material dispersion. The waveguide dispersion is caused by physical structure of optical fiber core and cladding. As a result of which different wavelengths propagate at different velocities in the fiber. Material dispersion is the dominant part of CD, caused by variation of the fiber refractive index with wavelength.

Optical fibers are inherently asymmetric on account of non-perfect conditions during the manufacturing process as well as environmental effects. As a result, light pulses in one polarization axis can move at different speeds to those in the other polarization axis. This will create a propagation delay between the optical pulses travelling in two polarization axis leading to PMD which becomes more critical at higher bit rates.

### 7.3 Nonlinear Effects

The response of optical fiber becomes nonlinear for intense light signals. The total polarization P induced by electric dipoles is given by Agarwal (2001),

$$P = \varepsilon_{0\,(X^{(1)}.E+x^{(2)}:EE+x^{(3)}\vdots\,EEE+\,.....)} \qquad (7)$$

Where ε0 is the vacuum permittivity and χ(j )( j=1,2,3,...) is jthorder susceptibility. The linear susceptibility χ(1)represents the dominant contribution to P and it is responsible for refractive index (n) and attenuation coefficient (α). The second order susceptibility χ(2)is responsible for nonlinear effects such as second harmonic generation and sum-frequency generation. However, these kinds of nonlinearities are negligible in silica glass fibers. The nonlinear effects that occur due to third-order susceptibility χ(3)are more dominant in the case of silica optical fiber. The nonlinear effects categorized under the Kerr effect as SPM, XPM, and FWM produce significant degradation in fiber optical communication systems, and hence in this work, only the Kerr nonlinearities are considered.

## 8. Conclusion

The OFDM technique is highly desirable for designing flexible and energy-efficient optical BackBone (BB) and Back Haul (BH) systems. It is also proposed as a future proof technique for the implementation of flexible resource allocation in CONs. Fiber impairment assessment and adaptive compensation are critical in such transport and CON implementations. If the OFDM signal is transmitted through optical fiber links, fiber linear and nonlinear impairments cause a cascading effect, increasing distortion and in turn BER degradation. Hence, the usage of OFDM in CONs necessitates the accurate assessment of impairments and their adaptive compensation. The existing analytical models in OOFDM systems consider only partial effects of fiber impairments. The proposed research aims to develop a comprehensive analytical model which includes the combined impact of various fiber impairments.

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