Master’s Thesis

Comparison of OFDM with Single Carrier in high-data rate optical communication systems

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Resum del projecte

En aquesta tesi, el rendiment de single carrier i OFDM sobre diferents situacions s’ha investigat. Adicionalment, dos tècniques de compensacions de no-linearitats com \textit{back-propagation} i \textit{RF pilot-tone} s’han implementat als nostres anàlisi per tal de veure el diferent rendiment que aquests mètodes poden aportar al rendiment de la senyal. Es pot veure que la mateixa millora s’ha assolit tant per SC com per OFDM, arribant a un augment en la màxima distància assolida d’aproximadament 18% i 13% pel cas de SC i OFDM respectivament quan els mètodes de \textit{backpropagation} i \textit{RF pilot-tone} s’apliquen junts. Els resultats conclouen que no hi ha diferències en la mitigació de no-linearitats en qualsevol tipus de format de modulació.

Principalment s’han considerat dos situacions en les nostres simulacions. Aquestes dos situacions són: \textit{dispersion managed link} i \textit{non-dispersion link}. El primer es va considerar degut al fet de que està extensament implementat en les actuals comunicacions òptiques i el segon s’ha considerat perquè es suposa que serà el futur més proper en els sistemes de comunicacions òptiques. Els resultats quan vem implementar el cas de \textit{non-dispersion link} van ser qualificat com els millors i més interessants que es van trobar. La raó és l’alta tolerància a les no-linearitats que es pot trobar en aquesta classe de situacions.

Després de tots els diferents anàlisi, els resultats han mostrat millor rendiment pel cas de single carrier tot i incurrint en una pitjor eficiència espectral. Amb l’ús conjunt de \textit{backpropagation} i \textit{RF pilot-tone}, OFDM pot assolir el mateix rendiment que single carrier sense cap tipus de compensació de no-linearitats, el qual significa que la diferència no es podria considerar com un problema difícil al qual poder enfrentar-s’hi.
Resumen del proyecto

En este proyecto, el rendimiento de single carrier y OFDM sobre diferentes escenarios se ha llevado a cabo. Además, dos técnicas de compensación de no-linearidades como backpropagation y RF pilot-tone se han implementado en nuestros análisis con el objetivo de ver las diferentes mejoras que pueden aportar en el rendimiento de la señal. Se puede ver que la misma mejora se alcanza tanto para SC y OFDM llegando a un aumento en la máxima distancia alcanzada de aproximadamente 18% y 13% para el caso de SC y OFDM respectivamente cuando backpropagation y RF pilot-tone son aplicadas conjuntamente. Los resultados concluyen que no se puede ver una diferencia en la compensación de no-linearidades para cualquier tipo de formato de modulación.

Principalmente dos escenarios se han considerado en todas nuestras simulaciones. Estos dos escenarios se componen de los llamados dispersion managed link y non-dispersion link. El primero de ellos se consideró debido a su extensa implementación en las actuales comunicaciones ópticas y el segundo es considerado porque se supone que será el futuro más próximo de los sistemas de comunicaciones ópticas. Los mejores y más interesantes resultados que se encontraron fueron cuando se consideró el caso del non-dispersion link. La razón reside en la alta tolerancia a las no-linearidades que se puede encontrar en este tipo de escenarios.

Después de todos nuestros análisis, los resultados han mostrado un mejor rendimiento siempre y cuando single carrier se transmitía incurriendo en una peor eficiencia espectral. Con el uso conjunto de las técnicas de backpropagation y RF pilot-tone OFDM puede alcanzar el mismo rendimiento que single carrier sin cualquier técnica de mitigación de no-linearidades, lo cual significa que la diferencia no es un aspecto inalcanzable con el que poder lidiar.
Abstract

In this thesis work, the performance of single carrier and OFDM along different scenarios is investigated. In addition, two nonlinear compensation techniques like backpropagation and RF pilot-tone were implemented in our analyses in order to see the different improvements that these methods can bring to the signal performance. It is shown that the same improvement can be achieved for SC and OFDM which can lead to an improvement at the maximum reach distance of approximately 18% and 13% for the SC and OFDM case respectively when backpropagation and RF pilot-tone technique are applied together. This results conclude that no difference in the nonlinear mitigation can be seen between any modulation format.

Two main scenarios where considered in all our simulations. This two scenarios are dispersion managed link and non-dispersion link. The first one was considered due to the fact that is widely deployed in actual optical communications and the second is considered because is supposed to be the near future in optical communication systems. Better and interesting results were found to the case were non-dispersion link was considered. The reason is the high nonlinear tolerance that can be found in this sort of scenarios.

After all the different simulation analyses, the results show better performance where a single carrier is transmitted incurring in a worst spectral efficiency. With the joint usage of backpropagation and RF pilot-tone technique OFDM can afford the same performance as single carrier without any nonlinear mitigation technique, which means that the difference is not a difficult issue to deal with.
1. Introduction

1.1. Background and Motivation

In modern technological history, different facts have pushed the telecommunication researches toward a new technologies in order to face up with the recent exponential growth in the required bandwidth, considering them to be the actual and future deployments in different telecommunication scenarios.

During the last decade, the telecommunication bubble in conjunction with the modern culture have increased the number of mobile devices (i.e: mobile phones, laptops, netbooks, tablet PC, etc) pointing Internet services as one of the main reason of this increasement. As it is already known, people have the "necessity" to be connected every time and everywhere to different applications as Facebook [1], Twitter [2], Youtube [3], and thus, a high-speed transmission systems are required if these services want to be covered. In this situation, optical fiber communications has emerged as a novel link to attain high data rates reaching the best relation between quality and maximum reach distance [4]. Actually, the most deployed links to provide all these services are the ones based on copper, either co-axial or twisted pair. Moreover, the preferred transmission format to increase bit rates over this infrastructure is digital subscriber line (DSL) technology. On the other hand, as it was aforementioned, optical fibers has strongly emerged as an alternative to all the implemented copper networks due to its much higher bandwith-distance product, enabling high-speed connections over longer distances.

The first generation of optical communications, considered at the beginning of this century, was the transmission systems where 10-Gb/s bit rates were used due to the low cost basis. Since then, capacities have steadily increased and the cost per transmitted bit has gradually decreased. Several solutions have been proposed in order to attain this high capacity at a high transmission data rates. One remarkable solution, founded in 1990, was the idea to transmit more than one channel over the transmission link, defined as wavelength division multiplexing (WDM) architecture. This technology enables to raise the amount of data traffic by multiplexing a number of lower capacity wavelength channels onto a single fiber. It is interesting to mention the importance that WDM systems have over long-haul optical transmissions because a remarkable decrease in the cost of
the transmitted bandwidth can be achieved.

Additional to this solution, other solutions have been proposed such as modulation formats and also at the receiver. At the beginning of this telecommunication bubble, coherent detection was introduced at the receiver in order to enhance the transmission distance [5]. The problem of coherent detection was that during 20 years was kept in stand-by because of the more efficient solution provided by direct-detection together with optical amplification at that time. After this period of time, coherent receiver has recently re-gained the interest in actual researches due to the digital signal processing (DSP) techniques. In a coherent receiver, not only the amplitude of the optical signal, but the full baseband optical field is transferred to the electronic domain. DSP implementation provides an improvement in signal’s robustness and increases the flexibility of the entire optical signal. Furthermore, it enables the equalization of nearly high amounts of chromatic dispersion and PMD. The new interest in coherent receiver in conjunction with DSP has pushed up the usage of advance modulation formats to realize high spectrally efficient transmission [6].

Multi-level modulation formats have attracted the interest in the last years because of the high spectral efficiency. The most important modulation format used in researches today is the so called POLMUX-16-QAM. When POLMUX is mentioned, we refer to polarization-multiplexed. This transmission format has become attractive as a result of the independent data modulation transmitted into each of the two orthogonal polarizations of an optical fiber. The main advantage from implementing a POLMUX transmission is doubling the spectral efficiency and halving the symbol rate in comparison to single-polarization modulation. Apart from the increasing interest in multi-level modulation formats, it is important to mention that there is raising interest in different nonlinear mitigation techniques due to the feasibility brought by the DSP-based receiver. In the last decade, several techniques have come out to deal with nonlinear impairments, such as self-phase modulation (SPM) and cross-phase modulation (XPM), which are considered the most limiting factors for a WDM long-haul optical system. Back-propagation (BP) and RF-pilot-based tone (RFP) have been demonstrated to be specially effective for orthogonal frequency division multiplexing (OFDM) [17], and recently its effectiveness has been studied for the case of single carrier.

As long as the spectral efficiency becomes the most considered target in optical communication systems, OFDM has exponentially grown as a central point in actual and future researches because of its better spectral efficiency. OFDM is also interesting because of its extensive use in broadband wired and wireless communication systems. Thus, the idea that OFDM could afford the same system performance in optical communications systems is supposed but needs to be analyzed. Although OFDM has gained popularity
in the past decade and has widely been implemented in numerous communication standards, the problem that OFDM has to be compared with SC transmission (which is the technique deployed in optical fiber systems) is still remaining. Few investigations have been focused on the debate regarding whether OFDM or single-carrier applying frequency domain equalizer (SCFDE) is superior. After all those investigations it may be premature to conclude which of both modulation formats can afford the best system performance, because an extensive study between the advantages and disadvantages versus the scenario where OFDM and SCFDE are performed is required.

The goal of the thesis presented here is to give an extensive and comprehensive comparison between the two aforementioned modulation formats. No clear conclusions have been reported in the last investigations of this topic in the last years not clarifying if the advantages given by OFDM can overcome its own disadvantages. Moreover, considerable simulation analyses have been done in order to study all possible scenarios where the comparison of SC and OFDM can be interesting. Due to the nonlinear influence in long-haul optical communications, two novel nonlinear mitigation techniques such as BP and RFP were applied in order to give a better performance and quantify the achievable improvements of these compensation techniques.

In this work, it is shown that BP and RFP can give a significant improvement in signal performance, well compensating for SPM and XPM respectively. Only simulated data was considered in order to analyze the comparison of both modulation formats. Furthermore, narrow optical filtering, different pulse-shape transmission, and the different effects by applying the two nonlinear compensation techniques alone were considered. As an outcome of this work, several publications appeared in conference proceedings and others have been submitted to leading conferences.


- A. Diaz et al., Comparison of Single Carrier and OFDM with ack-propagation and RF Pilot Tone for a 9x224 Gbs POLMUX-16QAM System, in IEEE Photonics, 2011.
1. Introduction


1.2. Thesis Outline

In this section a general overview of the thesis structure is given. The first part of the thesis consists of the Chapter 2 which review the basic concepts used in optical communications, taking a look at the transmitter, link, and receiver part of an optical system. At the beginning of Chapter 3 the basics of nonlinear mitigation techniques BP and RFP are explained. In this chapter the different simulation setups deployed in order to apply the two techniques are displayed. All the simulations done during this comprehensive comparison have been reported to the dispersion managed and non-dispersion managed scenarios. In Chapter 4 and 5 all the analyses referred to the dispersion managed links and non-dispersion managed links are respectively deployed. Finally, Chapter 6 summaries the most important conclusions found in this thesis and some future outlines are described if this work can be the basis of future investigations.
2. Theory

2.1. Modulation Formats

The most important aim of optical fiber communications is the interest to attain long reach distances and high transport capacities without incurring higher implementation costs per transmitted information bit while maintaining a high spectral efficiency. Among other enabling technologies, advanced optical modulation formats is playing a fundamental role in the development and design of modern wavelength division multiplexed (WDM) fiber systems.

In a WDM scenario is important to achieve remarkable cost reduction. Sharing the optical components among the WDM channels and increasing the per-channel data rates are two possible ways to accomplish this challenge. In addition to the low implementation cost, high spectral efficiency and capacity are also required and can be applied by several technologies [8].

Advance modulation formats\(^1\) are important because of their noise resilience, fiber propagation characteristics and resilience to narrowband optical filtering due to a casacde of optical add/drop multiplexers (OADMs).

The different modulation formats are classified depending on how the information is transported. Therefore, we distinguish between intensity, phase, and amplitude formats. In this section, we limit our attention to only the different modulation formats used in our simulations analysis.

- **Intensity**
  - OOK Nonreturn-to-Zero (NRZ)
  - OOK Return-to Zero (RZ)

- **Phase**
  - Binary Phase-Shift Keying (BPSK) and Differential-BPSK (DPSK)
  - Quaternary Phase-Shift Keying (QPSK) and Differential-QPSK (DQPSK)

\(^1\)In optical communications, advanced are all the formats that go beyond on-off-keying (OOK)
2. Theory

- Amplitude
  - Quaternary Amplitude Modulation (QAM)

2.1.1. Intensity Modulation Formats

**OOK Nonreturn-to Zero**

For quite a long time, OOK has been the most used modulation format for optical fiber communication systems. NRZ gained a momentum based in the low electrical bandwidth demanding for transmitters/receivers and, the resistance to LASER phase noise. Fig. 2.1 shows the transmitter scheme implemented when NRZ-OOK is used. The intensity modulator (in our system a Mach-Zender Modulator (MZM)) converts the OOK electric signal into an optical one at the same input data rate. The main advantage that NRZ provides is a narrower spectrum compared to other modulation formats such as RZ. Furthermore, its performance was found to be degraded more than other modulation formats in long-haul optical communications because of less resistance to fiber nonlinear impairments is afford [25],[26]. As a result, RZ has been deeply investigated in order to compare its advantages and performance against the NRZ format.

![NRZ-OOK transmitter scheme](image)

**Return-to Zero**

RZ-OOK transmitters (see Fig. 2.2) can be easily implemented for high-data rates by carving pulses out of an NRZ signal using an additional modulator, called pulse carver. Pulse carvers can be deployed by electroabsorption modulators (EAMs) or MZMs. Due to the variable absorption characteristics and residual chirp of EAMs, advanced RZ modulation formats are typically implemented using MZM-based pulse carvers. Depending on where a MZM is sinusoidally driven, different RZ cases can be deployed. This different
2.1. Modulation Formats

RZ cases are: 50%, 33%, and 66%-duty-cycle [8].
RZ spectrum due to the narrow symbol duration is broader than NRZ. As a consequence, RZ formats are more robust to nonlinear propagation distortions but less spectrally efficient. In [9], an extensive comparison between NRZ and RZ50 was carried out, concluding that RZ50 is able to improve in WDM-QPSK transmission experiment at an optimal launch power, 24% the NRZ performance. The main reason to explain this improvement is the advantage that a narrow optical filtering at the transmitter gives to RZ modulation format. After this narrower filtering, RZ pulse is converted into a high quality NRZ signal with less intersymbol interference compared with a conventional NRZ (see Fig. 2.3).

2.1.2. Phase Modulations

Differential Binary Phase-Shift Keying

Differential binary PSK encodes information on the binary phase change between adjacent bits: 1-bits are encoded onto a $\pi$ phase change, whereas 0-bits are represented without changing the previous phase value.

Fig. 2.4 depicts the optical DPSK transmitter. The data signal is differentially encoded at the transmitter because a differential encoding at the receiver can incurre in error...
2. Theory

Figure 2.4.: Setup implemented in a DBPSK transmitter

propagation. In addition, the phase of the optical field of a narrow-linewidth laser source is then flipped between 0 and \(\pi\) using the precoded data sequence. Another important element of the transmitter is the modulator, where usually a MZM is employed, since using this sort of modulators allows an exact phase modulation.

The most restrictive aspect at the receiver is the interference between bits. For that reason, a good avoidance to interferences is required because two optical fields can interfere destructively to each other whenever there is no phase change, and constructively whenever a phase change between subsequent bits.

Differential Quaternary Phase-Shift Keying

When we refer to phase modulation formats, we also find multilevel formats. DQPSK is the phase multilevel format that has attracted more attention in optical modulation formats. It consists in the addition of two more phase shifts at the DBPSK ones, which are \(\pi/2\) and \(-\pi/2\).

At the transmitter, two MZMs are required to operate as phase modulators. A LASER, before a splitter, feeds the two MZMs with equal intensity. The next stage is composed by an optical \(\pi/2\)-phase shifter that allow one of the paths to be shifted and then combined with the other path to produce a single output signal. The main advantage of this transmitter is that only binary electronic drive signals are required, giving an easier way to generate high speeds rather than the multilevel drive waveforms.

Is also important to mention the shape of a DQPSK spectrum. In the optical domain, the shape of the DQPSK is nearly the same as the one that DBPSK has, but the DQPSK spectrum is compressed in frequency due to the halved symbol rate. In conclusion, this compressed spectrum became a beneficial tool to achieve high spectral efficiencies in
2.1. Modulation Formats

WDM systems, increased tolerance to chromatic dispersion (CD), and a robustness to polarization mode dispersion (PMD).

2.1.3. Amplitude Modulations

Nowadays amplitude modulations formats are mainly focused on quadrature amplitude modulation (QAM) and multilevel modulation formats [27]. In the QAM case half the transmitted symbols are modulated with one frequency and the other half symbols are modulated with the same frequency but with a $\pi/2$ phase change. At the end the sum of both components will result in a QAM signal. As the definition noted, the modulated symbols with the pilot without phase would be defined as the in-phase component and the other phase-shifted component is called quadrature-phase component. Fig. 2.5 shows the different QAM constellations mostly used in communications.

In our simulation analyses, the 16-QAM format will be the chosen QAM transmitted modulation. The reason why we chose this QAM format is because M-ary QAM constellations enables data to reach higher data rates with a considerable spectral efficiency [11]. For example, the error-rate performance of 8-QAM is closer to the 16-QAM (only 0.5 dB better), but the data-rate is only 3/4 that of 16-QAM. Moreover, the data signal spectrum becomes much more narrower as the $M$ is increased. On the other hand, symbols are subjected to more errors due to noise and interference. Thus, one transmitted symbol is generated closer to neighbouring symbols which means that any interference could induce more errors as soon as the number of transmitted symbols are increased.

It is important to note that the usage of multilevel modulation formats increases the complexity in hardware implementation.

We carry out the analysis with 16-QAM because of the aforementioned advantages and because of its emergence as a promising candidate to attain high-data rates for long-haul networks [12].

Figure 2.5.: Examples of QAM constellations
2. Theory

2.2. Orthogonal Frequency Division Multiplexion vs. Single Carrier Transmission

Optical modulation techniques can be divided in two main groups: single-carrier (SC) modulation and multicarrier transmission. During the last years, optical frequency domain modulation (OFDM) modulation format has raised its importance in the optical field due to its exceptional quality to send information at high data rates. For this reason, the idea of giving a brief theoretical introduction of SC and OFDM establishing their advantages and disadvantages for a future comparison was supposed to be interesting.

2.2.1. Single Carrier

Single carrier (SC) technique has been widely employed in optical communication systems during the last three decades. During the 70s, many researches [10] focused their investigations in the fact that frequency domain processing techniques could also be implemented as a simplified equalization for SC systems. Additionally, the SC implementation implication/performance was found to be nearly the same as the one used for OFDM systems (only when FDE is considered).

One main characteristic of this systems, that becomes an advantage for SC, is its low measured peak-to-average ratio (PAPR) compared to the one presented in multicarrier systems. As a result, the SC transmitted spectrum and its forward performance are not severely affected by the nonlinear effects. Furthermore, this kind of systems are also important because of its robustness to frequency offset and phase noise.

Single carrier with frequency domain equalization (SC-FDE) has been chosen as the SC format for our simulation analysis. The potential shown by SC is one of the points to discuss in order to find if SC-FDE implementation is still being a real alternative to OFDM.

2.2.2. OFDM

Nowadays OFDM is extensively used in broadband wired and wireless communication systems because is an effective solution to intersymbol interference (ISI) caused by a dispersive channel.

Before OFDM, several techniques were utilized to transmit information over the frequency domain. Frequency Division Multiplexing (FDM) was the technique where the main signal is transmitted over a set of independent signals in the frequency domain, which are called subcarriers or tones [28]. It can be seen that if we use different subcarriers to transmit the entire data, we should divide the original data into many parallel streams,
2.2. Orthogonal Frequency Division Multiplexion vs. Single Carrier Transmission

one for each subcarrier. After that, each subcarrier is modulated with a conventional modulation scheme and combined together to form the FDM signal.

This can be understood as the theoretical beginning of the OFDM technique which will be discussed in this chapter. If the usage of large number of different subcarriers is desired, the necessity of a wide spectral space in the frequency domain is required, so that means being less spectral efficient. Thus OFDM appears as a solution to solve the mentioned problem. The idea was mainly supported by the concept of overlapping the different subcarriers with an orthogally condition between them, resulting in a more efficiency implementation than the FDM one.

While many details of OFDM are very complex, the basic concept of OFDM as we pointed before is quite simple. Data is transmitted in parallel on a number of different frequencies as is shown in Fig. 2.6. The different subcarrier frequencies are chosen in order to induce a mathematically orthogonal property over one OFDM symbol period. Both modulation and multiplexing functions are digitally achieved using an inverse fast fourier transform (IFFT) and therefore, the orthogonal signals can be generated precisely and in a very computational efficient way. Each subcarrier is centered at $f_k$ and separated by $1/T_s$ from its neighbours and because of its orthogonal property, the spectra of individual subcarriers will ideally appear without interference and without the need for analog filtering to separate the received subcarriers [29]. In Fig. 2.7, the spectrum of one OFDM subcarrier

![Figure 2.6.: OFDM time-domain transmission](image)
2. Theory

Figure 2.7.: OFDM signal in time (left) and frequency (right) domain

has a sinc form to better achieve the orthogonality between channels. A consequence of using this spectrum shapes is the sidelobes found along the total frequency range including many other subcarriers. This can be pointed as the main cause of one of the most important OFDM disadvantages: the sensitivity to frequency offset and phase noise [16]. At the end, we can note two important advantages of OFDM: the complexity of OFDM and of systems using serial modulation and frequency domain equalization, scale well as data rates and dispersion increase. The other important advantage is that this technique transfers the complexity of the transmitters and receivers from the analog to the digital domain. These advantages and other OFDM disadvantages can be discussed over this chapter.

2.2.3. Digital Signal Processing coherent receiver

Over the last years coherent optical receivers have gained considerable interest, becoming nowadays the most promising solution for future high-speed optical networks in optical communications. It is also important to mention the different past technologies implemented at the receiver to detect the signal. The most important considered technologies were:

- Noncoherent detection
- Differentially coherent detection
- Coherent detection

Noncoherent Detection

In noncoherent detection, the receiver computes decision variables based on a measurement of signal energy. This type of detection is usually deployed for on-off-keying (OFF),
2.2. Orthogonal Frequency Division Multiplexion vs. Single Carrier Transmission

Figure 2.8.: Differentially coherent phase detection of: (a) 2-DPSK and (b) $M$-DPSK multi-level amplitude-shift keying (ASK) and frequency-shift keying (FSK) [13]. However, there are some important limitations: (a) detection based on energy measurement allows signals to encode only one degree of freedom (DOF) per polarization per carrier, reducing spectral efficiency and power efficiency, and (b) the loss of phase information during detection.

**Differentially Coherent Detection**

The main characteristic that defines this second technique is that the receiver computes decision variables based on a measurement of differential phase between the symbol of interest and one or more reference symbol(s). In Fig. 2.8 the diagram of the idea explained in this paragraph for the DPSK case is shown. For example, if we compare binary differential phase-shift keying (DPSK) using differentially coherent detection and noncoherent OOK, at a bit error rate (BER) of $10^{-2}$, we will obtain a 2.8 dB of higher sensitivity in the case of DPSK.

**Coherent Detection**

The last and the most advanced technique explained in this section is called coherent detection. In this case, the receiver computes decision variables based on the recovery of the full electric field (amplitude and phase information).

Recently, the exponential growth of the interest in advanced modulation formats has increased the complexity requirement in coherent receivers. Traditionally, coherent receivers equipped with complicated PLLs (optical or electrical) fulfilled the purpose of knowing the carrier phase information in order to demodulate the received signal [13]. But recent researches in analog-to-digital conversion (ADC) technology have made possible to use digital signal processing (DSP) techniques to demodulate high-speed optically modulated signals.

The main challenge in coherent detection is locking the phase of the LO to the transmitter laser phase. This synchronization could be obtained using the different sort of PLL
mentioned before. That scenario had an important limitation: if a phase synchronization was desired, which was the high-speed nature of optically modulated signal, that speed will restricts the PLL. Its inherent feedback must respond very fast to any signal change, and for these reason, DSP has emerged as an interesting method to apply for phase synchronization because of the only phase tracking required (i.e Fig. 2.9), which can be implemented by a feedforward technique[15].

![Figure 2.9.: Example of a feedforward carrier-phase estimation](image)

Optical coherent receivers in conjunction with DSP has emerged as a promising technique enabling to attain high-information-rate in optical transmission systems. DSP appeared as the substitute to the PLL which was one of the barriers to use coherent receivers in the optical domain. With this deployment, several optical impairment mitigations can be addressed in the digital domain allowing a great flexibility in any optical network.

### 2.2.4. Orthogonal Frequency Division Multiplexing and Single Carrier comparison

The discussion between OFDM and SC in optical communications has become an important challenge in research. In the last section we have introduced both modulation formats in order to give a better idea of the most important theoretical concepts. After the introduction, a short comparison looking at the advantages and disadvantages is given in this section in order to establish a theoretical background and a basis for our numerical analysis.

**Main advantages and disadvantages**

After the last sections, both OFDM and SC advantages and disadvantages have been pointed but not further discussed. In the case of OFDM [16], the most important disadvantages are the high PAPR and the sensitivity to phase noise and frequency offset. Despite of OFDM disadvantages, also SC has its own limitations.

First of all, the implementation cost in the optical field appears as an important drawback for OFDM systems. One way to define this cost implementation is calculating the cost
2.2. Orthogonal Frequency Division Multiplexion vs. Single Carrier Transmission

complexity that would have an OFDM system. In [17], the complexity can be calculated as Eq. 2.1 where $C_{bit}$ is the number of subcarriers in OFDM or the number of points used in DFT-IDFT for each SCFDE block, $D$ is the accumulated CD per channel, $B$ is the baud rate, and $\alpha$ is the proportional constant. But this is not a complete disadvantage due to the nearly complexity that SC-FDE contributes, making both techniques interesting for systems with high-data rate.

$$C_{bit} \propto \log(N_{sc}), N_{sc} = \alpha DB$$ (2.1)

Looking that the cost implementation, for both systems are nearly the same. Another critical aspect that should be compared for optical communications is the effect of non-linearities. In long-haul single mode optical fiber, the PAPR is a fundamental disadvantage for OFDM, but this difference is only significant in systems where a dispersion compensation map is applied. In any case, this comparison is highly dependent on the studied scenario, for this reason our simulation analysis may result in a useful tool to decide the influence of non-linearities in each system.

Finally, the last important characteristics to be mentioned are the spectral efficiency in SC-FDE, the sensitivity to frequency offset and phase noise for OFDM. One main advantage of OFDM is the spectral efficiency that can offer to any system. The spectrum of SC-FDE is broader and the complexity in electrical and optical filters are increased as a result of the larger spectrum required to enclose the entire signal. As it was explained in the OFDM concepts, the main advantage of this modulation format is the orthogonality between subcarriers. But then, a strong accuracy in the phase of the receiver local oscillator is required because any difference compared to the carrier of the received signal can degrade system performance. Several researches have appeared with a novel technique to reduce this effect [18].

In summary, every comparison could result in an equal comparison because there is no strong feature that can definitively conclude which modulation is the best one. Due to the abstractness of each comparison, an additional issue should be carry out, focusing on numerical and analytical terms. Furthermore, the analyses are strongly dependent on the scenario studied and thus, is important to note that any conclusion given in this thesis is based on our researches.
Back-to-back simulations for both systems for different data-rate and modulation formats

The aim of this thesis is the comparison between SC and OFDM in order to figure out which of both modulation formats provide the best performance. One way to support our conclusions is basing them on the simulations analyses that are going to be carried out in the following chapters. Without exception, the theoretical performance, which means the best reachable performance of each modulation format is the first step that will take part in any future conclusion. This decision is going to be determined essentially taking a look at the performances and checking how closer are to the ideal case. For this reason, in Fig. 2.10 and in Fig. 2.11 the back-to-back simulations are plotted in order to set up the best attainable performance for SC and OFDM. The back-to-back simulations have been shown in terms of BER as a function of the optical signal-to-noise ratio (OSNR) for different modulation formats that will be used in our analyses.

2.3. Optical Link

An optical communication system (OCS) consists, as any other communication system, of three fundamental blocks: the transmitter, the communication channel and the receiver, as displayed in Fig. 2.12. The first part of the OCS is the optical transmitter, whose function is to convert an electrical signal into an optical one to be launched into the optical fiber, being this the communication channel. LASERS are usually used as optical sources because of their compact nature and the strong compatibility with optical fibers. An important transmitter design parameter is the optical power launched into the optical fiber. An optimal power launch power is required in order to make the signal possible to be received at the transmitter with the minimum effect of channel impairments.

The second main component of an OCS is the optical channel. The role of every communication channel, independent of its nature, is to transport the signal from the transmitter to the receiver. In our system, the channel is represented by the optical fiber. Optical fiber has emerged as the optimal channel communication for OCS due to the low losses that can affect the signal performance. Otherwise, optical fibers broaden signal because of the chromatic dispersion effect. Another source of signal distortion that can appear in optical fibers are the nonlinear effects. In the next sections, further details of all the impairments induced in optical fibers are going to be explained.

The last component is the optical receiver. The purpose of the optical receiver is to convert the optical signal into the electrical domain and to recover the transmitted data. Recovering the transmitted data means recover the distortions suffered in the signal be-
2.3. Optical Link

Figure 2.10.: Back to back performance for Single Carrier

Figure 2.11.: Back to back performance for OFDM
2. Theory

cause of the transmission through the fiber.

Figure 2.12.: Scheme of an Optical Communication System

2.3.1. Fiber Propagation

The propagation of a single polarization optical field $E(z,t)$ through an optical fiber is described by the Nonlinear Schrödinger Equation (NLSE) as given by [14]:

$$\frac{\partial E}{\partial z} + j\beta_2 \frac{\partial^2 E}{\partial t^2} = j\gamma |E|^2 E - \frac{\alpha}{2} E$$  \hspace{1cm} (2.2)

where $\alpha$ in [Np/km] is related to the attenuation that affects the signal power through the fiber; $\beta_2$ in [ps$^2$/(nm km)] is defined as the dispersion parameter and $\gamma$ in [(W km)$^{-1}$] is the nonlinear coefficient. Fiber propagation impairments are strongly dependent on the physical fiber characteristics. On the other hand, from Eq. 2.2 can be clearly seen that the signal power ($|E|^2$) is directly related to the nonlinear effects, represented by $\gamma$. This leads to the signal power dependence that is shown in Fig. 2.13 where nonlinearities increase the importance in signal performance as soon as the launch power is raised up. Due to quantum-mechanical lower bounds on optical amplifier noise, the received SNR can only be increased by launching higher signal power but is also affected by nonlinearities. For this reason, both linear and nonlinear effects will be studied in the next sections in order to understand the signal behavior through the fiber and how future techniques can mitigate nonlinearities.

2.3.2. Linear Impairments

Linear impairments can be defined as the basic but not the most important impairments that degrade signal performance, hence full compensation is achieved by modern coherent digital signal processing (DSP)-based receiver.

Fiber Attenuation

Once the signal is propagated into the fiber link, the power of the signal can suffer changes in the average power value due to the fiber attenuation. As [19], this loses can
2.3. Optical Link

Figure 2.13.: Example of predicted information spectral density limits per polarisation for non-linear transmission

be described by:

\[ \frac{dP}{dz} = -\alpha P \]  \hspace{1cm} (2.3)

where the parameter \( \alpha \) is the attenuation coefficient. If the integral in Eq. 2.3 is calculated and we assume that \( P_{in} \) is the input launch power to the fiber, the final equation that would describe the output signal power at a certain point of the fiber is given by:

\[ P(z) = P_0 \exp^{-\alpha z} \]  \hspace{1cm} (2.4)

where \( P_0 \) is the input power and \( z \) is the length where the output power is calculated. From Eq. 2.4 it can be seen that the optical output power decreases for longer distances. For this reason, when a long-haul optical network is deployed, the necessity of periodic optical amplifiers is strongly required in order to obtain an output signal power that allows the receiver to recover the entire signal.

Fiber losses depend on the wavelength of transmitted light [19]. In our case, where a wavelength near the 1.55 \( \mu \)m is applied, the fiber exhibited a loss about 0.2 dB/km which is the lowest value found in 1979 [20].

Chromatic Dispersion

The dispersion problem can be described as the pulse broadening result in the optical signal inserted into a dispersive channel such as the optical fiber. Moreover, the chromatic dispersion effect is the cause of the resulting inter-symbol-interference (ISI) which degrades the signal by corrupting the bits peak amplitude. When a 1-bit is transmitted, if the amplitude is raised over the normal value, it can result in a optical interference
within the neighbouring 0-bits. 

One of the most important constants that causes the dispersion effect is the mode propagation constant $\beta$ that can be described by:

$$\beta(\omega) = n(\omega) \frac{\omega}{c}$$

where $n(\omega)$ is the wavelength dependent refractive index, $\omega$ the angular frequency and $c$ is the speed of light. The dependency of $\beta(\omega)$ can be seen as a polynomial using a Taylor series expansion as is shown in [21].

$$\beta(\omega) \approx \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2} \beta_2(\omega - \omega_0)^2 + \frac{1}{6} \beta_3(\omega - \omega_0)^3 + \ldots \quad (2.5)$$

where $\beta_0 \text{[1/km]}$ denotes the constant phase shift, $\beta_1 \text{[ps/km]}$ corresponds to the speed at which the envelope of the pulse propoagates, $\beta_2 \text{[ps}^2/\text{km]}$ is called group velocity dispersion (GVD) and represents the change in group velocity with angular frequency $\omega$ and finally the parameter $\beta_3 \text{[ps}^3/\text{km]}$ is referred to the change of GVD with angular frequency. The dispersion parameter, which is the one that quantify the amount of chromatic dispersion that affects an optical signal is given by $D \text{[ps/(km km)]}$ and sometimes refered as the second derivative, $\beta_2$. Its relation to the GVD mentioned before is given by

$$D(z) = -\frac{2\pi c}{\lambda^2} \beta_2(z)$$

where $\lambda$ is the signal wavelength. Finally, the coefficient $\beta_3(z)$ of Eq. 2.5 is related to the dispersion slope $S(z)$ as the next equation shows

$$S(z) \equiv \frac{4\pi c}{\lambda^3} \beta_2(z) + \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3(z)$$

By applying the same concept as the periodic amplifiers, periodic dispersion compensation can be implemented. The resistance of a signal to CD helps to relax fiber specifications and minimizes the need for installing dispersion compensating fibers (DCF). But, in some scenarios the placement of periodic DCFs plays an important role. For this reason, further studies over DCFs are going to be realised in Chapter 4.

**Polarization-Mode Dispersion (PMD)**

In an optical single-mode fiber, the two signal polarizations are simultaneously propagated. Therefore, the output signal will be identically degenerated for both polarizations. Practically, due to the manufacturing imperfections and other variations the two polarizations can not be equally degraded and are slightly nondegenerated. The resulting two
polarization-eigenstates exhibit different group velocities and hence, the different group delay (DGD) is raised. This DGD effect is a dispersive pulse broadening that is commonly called polarization-mode dispersion (PMD).

The main challenge of this linear impairment is its stochastic nature that makes PMD prediction a really important issue. Nowadays, PMD compensation is not longer a considerable effect thanks to the equalization techniques that can fully avoid this phenomenon after the fiber propagation [22].

2.3.3. Nonlinear Impairments

The ultimate research in high capacity for optical communication systems has resulted in the widely usage of WDM technology where the influence of nonlinearities have become really important. Nonlinear impairments can be classified into two major groups: (I) Kerr nonlinearities and (II) Optical scattering.

Optical signals are strongly confined into the fiber core and thus, reaching high optical intensities. Due to that fact, the fiber’s index of refraction is affected and therefore signal-induced refractive index changes translate to changes of the signals’ optical phases. In this group of nonlinearities we can distinguish 3 subgroups: (I) self-phase modulation (SPM), (II) cross-phase modulation (XPM) and (III) four-wave mixing (FWM).

The last main group, optical scattering nonlinearities are caused by the interaction between the light and materials. Further information can be seen in [23] because in this thesis only special attention to Kerr nonlinearities has been given.

Self-Phase Modulation

Power variation inside the channel causes changes in the refractive index of the fiber causing a nonlinear phase shift defined as self-phase modulation (SPM). To better understand and quantify this effect, from Eq. 2.2 and without considering the chromatic dispersion phenomenon, the resulting equation is

$$\frac{\partial E}{\partial z} = j\gamma |E|^2 E - \frac{\alpha}{2},$$

where the first group of terms is related to the nonlinear effects but if a solution of this equation is found, the result can clearly show the nonlinear effects as is given by:

$$E(z, t) = E(0, t) \exp\left(\frac{-1}{2}\right) \exp\left(j\phi_{SPM}(z, t)\right).$$

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2. Theory

In this solution, the term that quantifies the SPM is defined as

$$\phi_{SPM}(z,t) = \gamma|E(0,t)|^2 \frac{1 - \exp(-\alpha z)}{\alpha}.$$ 

It is clear that the phase shift induced to the signal performance is dependent on the power of the signal. For this reason, the effect of SPM will be considerably more important at the beginning of the fiber or at the beginning of each span (after the power amplifier), when a high signal power value can be obtained.

**Cross-Phase Modulation**

SPM in conjunction with XPM limit the capacity of WDM transmission systems [24]. XPM effect is also caused by the intensity dependence of the refractive index but its nature is related to the transmission concept of a composite signal (WDM). The consequence of transmitting a WDM signal is the effect that one pulse can force into another pulse with different wavelength.

Once the transmission consists of two or more channels, the XPM that we would have to consider in our system will be described by:

$$\phi_{XPM,k}(z) = \gamma(|E_k(0)|^2 + c|E_{1-k}(0)|^2) \frac{1 - \exp(-\alpha z)}{\alpha},$$

where $k = 0,1$ depending on the channel and $c$ is a factor depending in the polarization of both pulses.

**Four-Wave Mixing**

FWM as the case of XPM is a consequence of a composite optical transmission system. The FWM is based in the interaction between four optical waves, that is the reason of its own name. FWM can be reduced either by reducing the power per channel or by preventing the perfect phase matching by increasing the CD or increasing the channel spacing.
3. Nonlinear mitigation of propagation effects

In the last chapter, a review of fiber propagation impairments hereafter considered has been reported. The state of the art technology shows that linear impairments can be fully compensated by using linear equalizer structures such as finite impulse response (FIR). The key role that DSP has emerged with, makes possible to implement several techniques that reduce and, in few occasions, fully compensate for nonlinearities. In this thesis, two novel compensation techniques are presented: (I) Radio frequency pilot-tone (RFP) and (II) backpropagation (BP).

3.1. Radio-frequency Pilot

3.1.1. Introduction

OFDM is a well-known modulation technique in the field of RF-communication and has recently attracted researchers interest. For this reason, several investigations have been carried out to adapt OFDM to optical systems and if needed to overcome its disadvantages where DSP plays an important role. One of the mentioned disadvantages in the last chapter was the sensitivity of OFDM to phase noise. The influence of phase noise on the OFDM system performance has been regarded, for WIFI and optical systems, in [30]. In these publications, the influence of phase noise was split into a multiplicative part, which is common to all the subcarriers and often referred as Common Phase Error (CPE), and an additive part, which is usually named as Inter-Carrier Interference (ICI). By comparing both effects, the main limiting factor is indentified to be CPE in the case where coherent detection receiver is deployed. CPE causes a constellation rotation affecting all transmitted symbols and, on the other hand, ICI is a consequence of the orthogonality loss between subcarriers. Therefore, many investigations have came out with different techniques [32, 33]. But in our analysis, only the RFP technique proposed in [18], has been implemented.

The main concept behind the RFP technique is the idea to revert the phase noise impairment by adding a RF-pilot tone in the middle of the OFDM spectrum at the transmitter.
3. Nonlinear mitigation of propagation effects

Placing this tone in the middle of the spectrum has the main advantage that does not affect the spectral efficiency thus no extra bandwidth is required. Furthermore, the pilot is distorted by phase noise in the same way as the signal, experiencing an inverse phase shift. The knowledge of pilot transmitted phase can be assumed and therefore simple phase correction can be done, applying this information in a back phase-shift to the data symbols.

The fundamental parameters that take part in this technique are: the pilot and in consequence its transmitted power value, the pilot frequency offset and the bandwidth of the recovery pilot filter. In OFDM as it was mentioned before, no pilot frequency offset is considered due to the placement of the pilot at the center of the OFDM spectrum. Moreover, it is important to note that the parameter related to the zero-forced subcarriers appears and must be considered for the pilot insertion.

The first parameter that is considered at the transmitter is the pilot frequency offset, which is a shift here referred to the center of the signal spectrum. In the case of OFDM, no phase shift was applied but, in our SC simulation analysis, the pilot frequency offset becomes an important factor.

Once the pilot is inserted, its transmitted power value is chosen through optimization. The transmitted pilot power is associated to the power-to-signal ratio (PSR), defined as

\[
\text{PSR}[dB] = 10 \log_{10} \left( \frac{P_{RF}}{P_{OFDM}} \right),
\]

where \( P_{RF} \) and \( P_{OFDM} \) represent the electrical power of the RF-pilot and the OFDM baseband, respectively. In the transmission, the optimization of the PSR becomes a key factor. If a low value of PSR is chosen, the RF-pilot is too weak and the amplified spontaneous emission (ASE) noise reduces the compensation quality at the receiver, whereas for higher PSR values, the optical signal-to-noise ratio (OSNR) of the signal becomes too low.

At the receiver, the pilot recovery is implemented at the DSP by downconverting and then filtering the received pilot. Using the extracted phase information to recover the signal rotation. As Fig. 3.1 depicts, the filter bandwidth is important depending on the PSR because at the receiver, the tone can be broader after channel propagation and as a consequence, an optimization in the filter bandwidth is required to perfectly filter the pilot information.
3.1. Radio-frequency Pilot

Figure 3.1.: Spectrum of a transmitted and received OFDM signal with the RF-pilot at:
(a) Transmitter and (b) Zoom of (a) [35]

3.1.2. Setup for Orthogonal Frequency Division Multiplexing

In Fig. 3.2 the OFDM scheme used in our simulation analysis is depicted. This scheme shows the three main parts of the system: the transmitter, the optical link and the receiver part for the RFP method.

The WDM signal is composed by 9 channels which are generated at a net symbol rate of 25 Gbaud. An overhead of 20% is added for forward error correction (FEC), 5% for training symbol sequences and 7.8% for the cyclic prefix added in OFDM. After the overhead addition, the gross symbol rate results being 34 Gbaud.

As depicted in Fig. 3.2, the next stage at the transmitter where the signal pass through, is the fast fourier transform (FFT) where a standard size of 256 was chosen. Inside this FFT size, 48 subcarriers were utilized for zero-padding, 206 were modulated and the 2 remaining corresponding to the Nyquist frequency. Afterwards, the pilot insertion in the center of the spectrum forces a zero-gap of 10 subcarriers. An optimization of the PSR should be carried out for every single launch power and in distance that one wants to analyze. For example, Fig. 3.3 shows the optimized PSR values for the power values that were chosen for our simulations. Then, the signal is fed to the digital-to-analog converter (DAC) and into a low-pass filter (LPF) with joint 3-dB bandwidth of 15.9 GHz. The system for OFDM employs a pre-emphasis stage for the compensation of the transmitter low-pass filtering impairments.

As it was explained in the last chapter, after the transmitter, the next component of an
3. Nonlinear mitigation of propagation effects

OCS is the optical link, where the signal is propagated until the optical receiver. In our simulations the optical link consists of several spans of 95 km of standard single-mode fiber (SSMF) with an Erbium Doped Fiber Amplifier (EDFA) with 6 dB of noise figure (NF). Further details of the fiber loss and Kerr nonlinearities parameters can be found in [34].

At the front-end, the signal is received by a coherent receiver and then fed into the analog-to-digital converter (ADC) which is set to identical values as the DAC used at the transmitter. Because of the pilot insertion at the transmitter, another stage to recover the pilot-tone is placed at the receiver. As it was pointed before, the filter bandwidth required to recover the pilot information is also optimized as the other RFP parameters (see Fig. 3.3).

3.1.3. Setup for Single Carrier

Several researches have been carried out applying the RFP technique for the OFDM case [35, 36, 38]. Recently, the idea of applying this technique to the case of SC has gained more interest [37]. For this reason, in this thesis the implementation of the pilot tone for the case of a SC has been considered in order to compare the benefits provided by RFP technique in both cases.

The WDM signal is generated at a net symbol rate of 25 Gbaud. The same overhead as in the OFDM case is added, but without the cyclic prefix, resulting in a symbol gross rate of 31.5 GBaud. After signal generation, the same stage as for the OFDM is placed, where the DAC in conjunction with a LPF with 3-dB bandwidth of 24 GHz are employed. In the
3.1. Radio-frequency Pilot

Figure 3.3.: PSR and RFP bandwidth optimization in a 16-QAM modulation system when RFP and BP are implemented

SC case, the RF pilot is implemented after the DAC and a required PSR was deployed. In this thesis, no zero-padding for the SC case was considered because the pilot was applied out of the signal spectrum, keeping in mind the idea of using more than one tone in this technique for future investigations. This frequency offset was optimized, showing an optimal value of 24 GHz as it can be seen in Fig. 3.4. At the end of the transmitter, depending on the generated modulation used (RZ50 or NRZ) a pulse carver would be utilized or not.

Figure 3.4.: SC spectrum after RFP addition

In Fig. 3.5 the same optical link as the one used in OFDM is reported, because it does not
3. Nonlinear mitigation of propagation effects

depend on which modulation is transmitted. Finally, at the coherent receiver a bank of 4 ADC is applied to receive the transmitted signal. At the receiver the ADC parameters can not be the same as the ones at the DAC due to the RFP insertion. For this reason in our analyses, a larger ADC filter bandwidth of 23.1 GHz is required, incurring in a less noise filtered efficiency as a consequence of ASE induced in this filtering. Then, the RFP compensation is performed in order to recover the induced phase shift and apply it to recover the transmitted data symbols. The same RFP bandwidth optimization at the receiver should be done in order to fully recover the pilot.

Figure 3.5.: SC system applying RFP technique

3.2. Back-propagation

3.2.1. Introduction

While the last section has reviewed one of the most important compensation techniques to mitigate XPM, back-propagation method has gained more interest in the last years as a novel technique for SPM compensation [39, 40, 41]. In Section 2.3.1 the NLSE has been introduced, and from Eq. 2.2 it can be clearly seen that in the absence of noise, the signal can be recovered by inverting the NLSE equation, defining this process as "backpropagating". We write the backpropagate equation as

$$\frac{\partial E}{\partial z} = (-\hat{D} - \hat{N})E,$$

where $\hat{D}$ is the linear and $\hat{N}$ the nonlinear part. This operation is equivalent as inverting the propagation parameters that cause the nonlinearities which are $\alpha$, $\beta_2$ and $\gamma$. Fig. 3.6 shows more clearly the concept behind BP. An exact solution to the last equation is
given by [39] having as a result

\[ E(z + h, t) = \exp(h[\hat{D} + \hat{N}])E(z, t) \]

where \( t \) is the time, \( z \) is the exact position in each span and \( h \) the step size. The exact solution to this equation is hardly affordable and therefore an approximation by the Split-Step Fourier Method (SSFM) is used.

\[ \exp(h[\hat{D} + \hat{N}])E(z, t) \approx \exp(h\hat{D}) \exp(h\hat{N})E(z, t) \quad (3.2) \]

which is valid as long as the step size \( h \) is small enough. Therefore, every step is composed of a linear and nonlinear step. In each step of every span the algorithm shown in Fig. 3.7 is applied. The linear step consists in the dispersion compensation applied into the frequency domain by

\[ E(z + h, t) = \mathcal{F}^{-1}\{\mathcal{F}\{E(z, t).H\}\}, \]

where \( H = \exp(jh\beta_2(2\pi f)^2/2) \). This step is similar as the dispersion compensation employed by a standard linear frequency domain equalizer (FDE) where the CD has to be estimated and then compensated. On the other hand, the power dependent nonlinear mitigation can be given by this equation

\[ E(z + h, t) = E(z, t).\exp(-j\gamma|E(z, t)|^2) \]

Finally, the power normalization is the result of the amplifiers located after each span. It is important to mention that BP requires an accurate knowledge of the fiber link parameters in order to invert the value of these parameters in the BP implementation. In addition, the span length, the fiber parameters, the dispersion map and the launch power have to be known by the receiver.
Nonlinear Channel Models

As the power is not constant through the span length due to the fiber losses, large steps cannot be used with the last equation mentioned in the previous section. However, the solution in Eq. 3.2 can be refined by evaluating the nonlinear part with a constant envelope profile and varying the intensity. Once this modification is applied, larger steps sizes can be used because the power does not have to be constant throughout the step as it was in the case before. The approximated solution becomes

$$E(z + h, t) \approx \exp(h \hat{D}) \exp(h_N \hat{N}) E(z, t), \quad (3.3)$$

where $h_N$ is the nonlinear step size. In [39], three nonlinear models where presented depending on the position of the linear and nonlinear parts in the solution of the NLSE. The Wiener model performs first the linear before the nonlinear one, having as a consequence the chromatic dispersion compensation at the beginning of this model. The opposite to the last model is done by the Hammerstein model where the nonlinear part precedes the linear one. Finally, the third model called Wiener-Hammerstein is a cascade of the two previous models and therefore is composed by three blocks. At the beginning, a linear step is performed compensating for CD. Then, the nonlinear compensation is performed. At the end, the remaining CD is compensated in an additional step.

Step Modes

The step mode can be defined as a key parameter inside BP algorithm and thus, an optimization for the nonlinear and linear step value is required. The main challenge in the step value is the fact that an increment in the number of steps per spans results in better accuracy and performance of the BP algorithm, but incurring in a higher computational complexity not implementable in real-time. Therefore an optimal value, between the improved performance and the reduced complexity requirements, must be defined. The first trivial step mode derivates from Eq. 3.2, where the nonlinear length is equal to the linear part. In this mode, the span is divided into $N$ equal parts. Hence, $h_N = h =$
3.2. Back-propagation

$L/N$, where $L$ is the total span length and $N$ the number of steps. This method hardly estimates the signal power where small number of steps per span are utilized. As soon as the $N$ value is increased, better power estimation is approached, reaching a perfect power approximation for $N \to \infty$. As mentioned previously in this thesis, the nonlinear effects are power dependent. The power behaviour decreases exponentially, neglecting the nonlinear impact when low power values are assumed. Therefore, it is easy to find the span length where the signal power plays a non negligible role. This length is called effective length and can be calculated as follows

$$L_{eff} = \int_0^L P(z)dz = \int_0^L P_0 \exp(-\alpha z)dz = \frac{1 - \exp(-\alpha z)}{\alpha} \quad (3.4)$$

The second approach is to divide the span into equal steps and then calculate the effective length in each step by using the equation mentioned before. In this case, a perfect power estimation is found due to the fact that the surface under the power curve is equal to the power in the effective length. An illustrative comparison is shown in Fig. 3.8.

3.2.2. Setup for Orthogonal Frequency Division Multiplexing and Single Carrier

In Section 3.1 different setups for OFDM and for the SC case have been deployed due to the implementation differences in both cases. The transmitter scheme is the same as in any other usual transmitters without BP implementation, due to the nature that the BP is a compensation technique which is placed at the receiver [42]. Only the knowledge of fiber link parameters are an important factor, and for this reason the parameters of Table 3.1 should be transmitted and utilized at the BP stage in the DSP.

In Fig. 3.9 the DSP configuration at the receiver is shown. This can be described as
3. Nonlinear mitigation of propagation effects

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation [dB/km]</td>
<td>0.19</td>
</tr>
<tr>
<td>Dispersion Coefficient at 1550 nm [ps/nm/km]</td>
<td>16.8</td>
</tr>
<tr>
<td>Dispersion Slope [ps/nm²/km]</td>
<td>0.057</td>
</tr>
<tr>
<td>Effective Core Area [µm²]</td>
<td>80</td>
</tr>
<tr>
<td>Nonlinear Coefficient $\gamma$ [1/(W.km)]</td>
<td>1.14</td>
</tr>
</tbody>
</table>

Table 3.1.: Fiber Link parameters [34]

the most important part in the BP technique, because is where the BP algorithm and therefore the SPM compensation are applied. When the signal is coherently received at the receiver, each channel is filtered out and synchronized in order to fed it into the BP stage where the algorithm is compensating for SPM in each single channel.

Figure 3.9.: Receiver DSP block diagram for SC and OFDM case
4. Dispersion-managed link

4.1. Introduction

Lin et al. were the first to propose the usage of the dispersion compensating fiber (DCF) in 1980 [44]. The first demonstration of the use of DCF was in 1992 [45]. Since then, dispersion management (DM) techniques have been studied in particular because of their effectiveness in mitigating effects such as CD. During the beginning of the last decade, several DM techniques have been considered as an alternative to DCF. However, conventional DCF have been worldwide deployed in the order of more than hundreds of thousands modules becoming then, as the most widespread technique for CD compensation.

As explained in Section 2.2.3, with the emerging of DSP-based technology applied to coherent receiver, the compensation of CD using DM schemes is an option that will be no longer considered for future optical systems. At the moment, a major issue concerns the existing long-haul optical transmission links (usually employed at line rates of 10-Gb/s), where dispersion compensation components (mainly DCF) have been employed. Since it would be not cost-efficient to replace actual optical communication systems, in this work we will investigate the performance of a POLMUX signal received by a DSP-based coherent receiver for the case of DM. The other option called non-dispersion managed link (NDM) will be analyzed in Chapter 5.

4.2. Performance of Dispersion Management System

As we previously pointed out, data-rate of 10-Gb/s or 40-Gb/s are currently implemented into long-haul networks employing DM solution. In order to compensate for the overall accumulated CD, DCF method was developed as a considerable effective option to solve this problem.

The idea behind DCF method is simple and it is illustrated in Fig. 4.1. Each span basically consists of two kinds of fibers; one is deployed as a SSMF which is the transmission fiber, and a second DCF that has positive second and third-order dispersion values (DCF), act as CD canceler in the optical domain. This implementation is the chosen one
for our following simulations. Another example of DM implementation scheme are the ones used in transoceanic communications which are composed by Dispersion-Managed Cables (DMCs) [43]. As Fig. 4.1 shows, the fiber length of the DCF is not specified as it depends on the scheme we want to use for the dispersion map, which is the evolution of the dispersion compensation along the link. The design of a dispersion map is strictly dependent on the nonlinear effects we want to compensate for. Two important parameters in a dispersion maps needs to be considered: residual and inline compensation. No pre-compensation was considered in our analyses.

After each span, residual dispersion can be expressed as

\[ D_{\text{res}}(\lambda) = D_{\text{TF}}(\lambda)L_{\text{TF}} + D_{\text{DCF}}(\lambda)L_{\text{DCF}}, \quad (4.1) \]

where \( D_{\text{TF}}(\lambda) \) and \( D_{\text{DCF}}(\lambda) \) are the dispersion coefficients of the transmission fiber and DCF as function of the wavelength \( \lambda \), while \( L_{\text{TF}} \) and \( L_{\text{DCF}} \) are the lengths of the transmission fiber and DCF, respectively. Fig. 4.2 shows two kinds of different dispersion maps design. In our case, we considered the compensation for the 90\% of the accumulated CD per span and therefore, a 10\% of residual dispersion remain after each span. Once the desired amount of residual dispersion is decided, the resulting DCF length can be calculated and for our specific link, it corresponds to 8.45 km. Typically, in a DM scheme the length of the SSMF is around 100km while for a DCF length must be considerable shorter because of its physical parameters of the DCF.

As explained in [21], DCF has a smaller core effective area and different core index profile in comparison to SSMF. In addition, the triple cladding index profile forces a larger part of the optical field to propagate in the cladding and thus, an increasement in the amount of waveguide dispersion is found resulting than in large dispersion values. Another reason why short lengths are chosen for DCF is the high attenuation value (see Table 4.1) and
4.2. Performance of Dispersion Management System

Figure 4.2.: Different dispersion compensation schemes for optical communications systems [21]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Longitude [km]</td>
<td>8.45</td>
</tr>
<tr>
<td>Insertion Loss [dB/km]</td>
<td>0.5</td>
</tr>
<tr>
<td>Dispersion Coefficient at 1550 nm [ps/km/nm]</td>
<td>-170</td>
</tr>
<tr>
<td>Nonlinear Coefficient $\gamma$ [1/(W.km)]</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Table 4.1.: Typical parameters of a Dispersion Compensation Fiber [43]

Besides the importance of choosing the right dispersion map in our DM scheme, there are considerable effects such as the loss, PMD effects, and nonlinear impairment tolerance which should be take into account. In this section, special attention only to the nonlinear tolerance is paid, the loss is no longer considered a problem since low values of DCF lengths are choosen [46].

In Chapter 3, an extensive review of nonlinear effects has been reported. Nonlinear impairments are among the strongest limiting factors of current optical networks. Therefore, an analysis considering the nonlinear performance in DCF is important to be considered [47],[48]. K.Forozesh et al. reported that the nonlinear tolerance with respect to both SPM and XPM is severely degraded when inline dispersion compensation is employed [49]. For these reasons, the removal of the DCF modules presents two main advantages: (I) it allows maximum reachable distance as CD also reduces the nonlinear inter-channel interactions (i.e. effects such as XPM become less important) and (II) it rises the flexibility of the link. Moreover the system design cost is reduced due to the DCF removal.

In a near future, optical links will be deployed without DCF modules. This new concept is commonly identified by the name non-dispersion managed (NDM) link and it has been shown in [50] that it provides a better performance compared to DM. In Chapter 5 a better understanding of NDM systems will be given.
4. Dispersion-managed link

4.3. Pulse Comparison of Single Carrier and OFDM in DM Systems

In this section, we analyze the performance of RZ50, NRZ, root raised-cosine filter (RRC) [51] pulse shapes and OFDM, for an optical system where a DM compensation scheme is employed. This analysis is carried out for different modulation formats on a SSMF transmission link. The performance of 50-Gb/s DP-BPSK, 100-Gb/s DP-QPSK and 200-Gb/s DP-16-QAM were evaluated and compared for single carrier and OFDM transmission. The simulation setup used for this simulation analysis is shown in [42], having the same symbol rate for all the modulation formats mentioned before.

The study of 9 equally modulated and co-propagation channels within a 50-GHz grid is focused on the nonlinear tolerance and the spectral efficiency properties when inline dispersion compensation is employed. Concerning the pulse-shaping obtained by using several roll-off values, only the roll-off values $\alpha = 0.3, 0.5$ and 0.7 are evaluated. The reasons of this range of values for $\alpha$ is the following: if we had employed lower values, the system performance would have been limited by the timing jitter. Moreover, values for $\alpha$ higher than 0.7 would have been meaningless, since the selected optical filter at transmitter would have filtered out the excess spectrum generated by higher $\alpha$ values.

At the receiver, a target BER of $10^{-2}$ was assumed, which corresponds to the current FEC limit for 20% overhead and soft decoding. Fig. 4.3 shows the maximum reach in a DM link as function of the launch power for the different modulation formats aforementioned. It can be clearly seen that the best performance are obtained by RZ50 pulse shape, which reaches the longest distance for all the modulation formats, while the shortest corresponds to the OFDM case. The increased distance was calculated between the lowest and the maximum distance reach resulting in 9%, 6% and 5% for DP-BPSK, DP-QPSK and DP-16QAM, respectively. For these calculations, OFDM was no longer considered due to the low performance compared to the other pulse shapes. The poor results obtained by OFDM can be explained as in [52]. In fact, the combination of high PAPR in OFDM systems in conjunction with DM links leads to a coherently addition of nonlinear distortions from span to span giving a worse performance.

4.4. Nonlinear Mitigation for DM links

In last section, we considered the effects of using different pulse shapes on the nonlinear performance of several modulation format over DM links. We already mentioned that BP and RFP have been identified among the most promising techniques for nonlinear
4.4. Nonlinear Mitigation for DM links

- (a) DP-BPSK
- (b) DP-QPSK
- (c) DP-16QAM

Figure 4.3.: Maximum reach distance versus launch power for 9 WDM channels through a DM link [42]
4. Dispersion-managed link

Figure 4.4.: Full dispersion compensation map

compensation. At the time we are writing, no comprehensive investigations on the mitigation of nonlinear effects over DM scenarios has been reported. Regardless the poor tolerance against nonlinear impairments, DM link are still the most deployed scheme in actual optical communications transmissions and therefore an extensive investigation of nonlinear mitigation is required.

4.4.1. Back-propagation for DM systems

In Section 4.2 the concept of DM compensation was introduced. Depending on the quantity of CD compensated, the dispersion map varies from one system to another. For example, as illustrated in Fig. 4.4, the whole communication link results in a symmetric span, and CD and power value are equal after each span. If this dispersion map is implemented, the BP would be equivalent to several nonlinear steps without linear steps between them. Therefore, it can be clearly seen that the nonlinear steps can be merged into one single step, and as a consequence, only one single BP for the whole link is required.

Fig. 4.4 shows the dispersion map of a fully compensated link composed of 8 spans each of 95 km SSMF and 8.45 km of DCF. As it is depicts in Fig. 4.4 all the spans have similar CD behaviour. The 8 spans of the link can be merged into a single span and the BP can be performed in one single step. Zied et al. showed a computational complexity reduction under the assumption that the nonlinearity of the DCF is negligible [53]. In order to verify that this complexity reduction does not lower the performance, a simulation of 2 WDM POLMUX 16-QAM channels at a 224-Gb/s over a fully inline compensated link was carried out. Fig. 4.5 displays the post-processing simulated data for the case mentioned before. From our simulations we can conclude that the results applying the BP algorithm with 15 steps are comparable to the ones where one single
4.4. Nonlinear Mitigation for DM links

step per link is applied.

Figure 4.5.: BP computational complexity reduction demonstration. Comparison between applying BP with 15 and 1 steps

Nowadays fully compensation maps are not considered suitable for long-haul optical communications because by fully compensating for the CD we reduce the overall system performance making it less robust against nonlinearities. Since now, Fig. 4.6 is going to be considered for the rest of this chapter as the referring dispersion map, where a 90% inline compensation is employed. Starting from the point on the right (indicated with the letter A) and tracing an horizontal line towards left, a series of points over the link with the same amount of CD can be identified. Therefore, the fact that several points have the same CD value can be exploited in order to reduce the BP operation complexity over the transmission link. All the points where an equal CD value can be identified in Fig. 4.6 are not located at the beginning of each span. With respect to the back-propagation, this value corresponds to the CD at a certain point of the span, being located within the nonlinear length\(^1\). As reported in [54], the BP performance (usually measured in terms of improved nonlinear tolerance) is at least similar to the performance when the Wiener model is deployed, if the nonlinear step is performed within the nonlinear length. According to these results, the last 4 spans of the link in Fig. 4.6 can be merged together and the nonlinear compensation can be performed within a unique step over them. Furthermore, the value of CD at point A can correspond to a CD value at an optimal point of another span, so that the nonlinear compensation is optimized for this span.

We also point out that if the under-compensation fraction is smaller, more steps can be packed together, reducing the complexity of the BP algorithm. As it was mentioned

\(^1\)Nonlinear Length depends on the fiber loss parameter and the span length [19]
4. Dispersion-managed link

Figure 4.6.: Dispersion compensation map deployed in our simulations

before, a residual dispersion has to be compensated at the end of the hole optical link because not full compensation was done. This residual CD value can be easily compensated by a Time Domain Equalizer (TDE) due to the small reaming CD values. For the dispersion compensation map displayed in Fig. 4.6, BP performs the nonlinear compensation as follows. Firstly, the accumulated CD of the last span till the CD value indicated by A is compensated in one single linear BP step. Afterwards, the nonlinear compensation through the BP algorithm over the last and the following 3 neighbours spans is performed. Another compensation over the following 3 neighbours spans should be done. Finally, the residual CD is compensated as we mentioned before by applying a TDE with an increased number of taps.

4.4.2. RFP for DM link

Alternative to BP, in Section 3.1 the RFP technique has been pointed as another important technique for nonlinear impairments mitigation. As it was explained in the chapter before, RFP has been proposed for XPM mitigation [18]. Furthermore DM was found to increase the importance of nonlinearities, especially of XPM [56]. For this reason, the interest of RFP implementation in a DM scheme became to be significant.

As soon as OFDM emerged as a promising technique for long-haul communication systems, the amount of researches in this topic rose dramatically. Since DM have been deployed worldwide, it becomes meaningful to focus on the performance of such a modulation formats over this kind of link. So far, no comprehensive researches for single carrier in DM systems applying RFP technique were carried out. In [42] an extensive study on the XPM compensation in a CO-OFDM system was reported, investigating
different fibers and dispersion management options. It was observed that in systems with in-line dispersion compensation, the nonlinear distortions are correlated resulting in a less nonlinear efficiency and thus, the RFP-based compensation is imperceptibly effective for any evaluated constellation sizes for a OFDM system.

On the other hand, besides the application of RFP to multi-carrier transmission, we considered important the effect of this compensation technique applied to single carrier transmission, where so far only few investigations have been carried out. Afterwards, a comprehensive comparison between the effects of RFP compensation with SC and OFDM systems over DM maps is hereafter presented.

4.5. 9x224 Gb/s POLMUX-16QAM system with Nonlinear Mitigation

In order to further investigate the effects of nonlinear mitigation over a dispersion compensation scheme, a 9 WDM POLMUX-16QAM at 200-Gb/s channels were transmitted over a DM link employing SSMF. The performance of a 200-Gb/s POLMUX-16QAM OFDM system is evaluated over the same system scheme applied in [61]. In this section, different configurations are presented one after another applying: (I) only BP, (II) only RFP and (III) both techniques.

For the SC, only the NRZ digital format is considered in the comparison analysis. From Fig. 4.3 when 16-QAM is performed, we can clearly see that NRZ and RZ50 have nearly the same performance and therefore the investigation over both modulation formats would result in a redundant information. All simulations are presented in terms of maximum reachable distance as a function of launch power where the target bit error rate assumed in our system was $10^{-2}$.

Fig. 4.7(a) depicts the implementation of the above described configurations to analyze the reliance of these techniques against SPM and XPM compensation for a SC system. It has been mentioned in this chapter that XPM effect plays a significant limiting role in DM links, for this reason RFP gives us a better performance compensating most of the XPM effects. In the case when BP is applied, the performance is nearly the same as NRZ case below a launch power value of 1 dBm. For higher power values, the mitigation of SPM gives better improvement due to the raising importance of nonlinearities for high launch power values. We can conclude that no XPM compensation is done applying only BP for the DM link case. Finally we reported the same study for the OFDM case as is displayed in Fig. 4.7(b). No improvement can be seen for launch power values under 1 dBm applying either BP or RFP. For higher power values the BP technique brings better performance due to SPM compensation. On the other hand, RFP can not afford
a strong XPM compensation because high values of XPM present within DM link. For this reason, the conclusion drawn for the SC case is valid also for OFDM, where actually the improvement is even smaller.

Figure 4.7.: Maximum reach distance versus launch power for 9 WDM channels transmission in a DM links for: (a) Single Carrier and (b) OFDM
5. Non-dispersion-managed link

5.1. Introduction

In last chapter an explanation of the basic principles of DM links was reported. As we already mentioned, in a near future, all DM links will be substituted with NDM ones, which are characterized by a significant simplification along the optimal link and by an increased complexity of the receiver by means of the DSP. This flexibility relies on the potential that DSP can provide to optical communications. Implementing a DSP-based coherent receiver shows an improvement in the system efficiency because the complexity is moved to the receiver and thus NDMs links will become attractive for future long-haul communications.

In this chapter we firstly introduce the main aspects dealing with this kind of systems and secondly we show the performance assessment by means of post-processing the simulated data. Finally, a comparison of NDM against DM will be carried out highlighting the advantages and disadvantages of both systems.

5.2. Performance of Non-Managed Dispersion Systems

Non-dispersion managed systems have been found to be more interesting than DM systems because the electronic dispersion compensation (EDC) approach a better CD compensation rather than dispersion compensation schemes in presence of substantial nonlinearities (mostly XPM) [57].

Recently, several researches have been focused in WDM schemes in order to reach high capacity values for long-haul optical communications. When a WDM transmission signal is fed into the fiber, the XPM impairments raised exponentially their effects over the transmitted signal. Therefore, apart from SPM, another impairment would degrade the signal performance, which is the case of XPM. In last chapter the interaction between CD and nonlinearities was considered. As soon as no inline CD compensation is performed, a better nonlinear tolerance can be found in this kind of systems. K. Forozesh et al. investigated the differences between implementing DM and NDM links, showing that when...
DCF are removed from the transmission line, all impairments are completely uncorrelated and average out [49]. The averaging in this perturbations can lead to the high nonlinear tolerance that was mentioned before. In this case, the simulations were considered for OFDM signals transmitted over a SSMF fiber, which resulted in a degraded performance when DM is employed.

It is clear that in order to further improve the signal maximum reach distance the advantages that a DSP-based receiver can bring into our system should be considered as the best ones to obtain a better performance. As it was done in the last Chapter 4, RFP and BP techniques will be considered in our following analyses. The effects of RFP and BP mitigation techniques can be better considered for the case of NDM transmission links due to the fact that SPM compensation for BP has a higher efficiency and RFP proved to be better for NDM system since the effect of XPM is reduced compared to the DM case [56]. Looking at the advantages of both mitigation techniques, in our simulations we examined the improvement applying RFP and BP together in different scenarios in order to verify if the joint usage of RFP and BP can mitigate for most of the nonlinear impairments (SPM and XPM).

5.3. Narrow Optical Filtering on 200-Gbit/s DP-16-QAM

It is well known that techniques like BP and RFP (see Chapter 2) are considered as novel methods in the nonlinear compensation of an optical field. Additionally, there has been significant interest in reducing the effect of nonlinearities by optimizing pulse shaping [58, 51, 59]. Despite all these researches, the aim of the simulations carried out in this section is to test the susceptibility of the pulse shaping to narrow optical filtering coming from a cascade of reconfigurable optical add/drop multiplexers (ROADMs). The concatenation of ROADMs was emulated by a single band-pass filter (BPF) at the transmitter which is expected to be the worst case scenario in terms of performance when distributed filtering over the link is employed. In these simulations a dual polarization 16-QAM 200-Gb/s was chosen for NRZ, RZ50 and RRC modulation formats. Moreover two different types of fiber link were considered: SSMF and large effective area fiber (LEAF).

The performance of 200-Gbit/s DP-16-QAM with different pulse shapes and for different transmitter optical filter bandwidth at the transmitter is evaluated. The same transmitter setup as the one in Section 4.3 was used. The optical link consists of a variable number of spans of 95 km of SSMF or LEAF, each with an EDFA of 6 dB of NF. In order to focus on the nonlinear effects, neither the transmitter LASER nor the local oscillator are assumed to generate LASER phase noise.
5.4. Comparison performance of Single Carrier and OFDM in NDM systems

The nonlinear tolerance of 220-Gb/s DP-16-QAM systems with 9 WDM channels is evaluated when 34 GHz, 38 GHz and 42 GHz transmitter optical BPF are used, corresponding to a 3 and 8 cascaded filters (for 38 GHz and 42 GHz), respectively. For all the simulations, only the roll-off factor of 0.3 is assumed for RRC case. In Section 4.3 it was shown that the relation of efficiency versus best maximum reach distance is the best when roll-off factor equal to 0.3 is transmitted and for this reason in these simulations is going to be considered the only case for RRC. Although a lower roll-off decreases the bandwidth occupation, it introduces penalties due to its low timing jitter tolerance.

Fig. 5.1 shows the maximum transmission reached distance as a function of the launch power for SSMF and LEAF fibers. In both cases, the maximum reach distance was calculated assuming a FEC limit of $10^{-2}$. Similar to the results presented in Section 4.3 when SSMF is the optical link studied, the RZ50 presents the highest performance due to the best nonlinear tolerance. However, this nonlinear tolerance property has a strong dependence on the filter bandwidth applied at the transmitter. The difference between the maximum reach for 34 GHz and 42 GHz is about 140 km, corresponding to a relative decrease in distance of 8.1% when the filter bandwidth becomes narrower. For the NRZ case this decrease corresponds to 4%, and for the RRC pulse shape, the effect of a narrowing filter bandwidth is negligible. On the other hand, when LEAF is implemented instead of SSMF the results show a lower reach distance for all pulse shapes. The lower dispersion parameter of the LEAF causes a higher coherence between the nonlinear regions, which can be compared to the case when DM links are considered. For LEAF, the difference between the considered filter bandwidths is not apparently clear as for SSMF. That suggests a less benefit of pulse shaping for LEAF than for SSMF.

5.4. Comparison performance of Single Carrier and OFDM in NDM systems

In the last chapter, the same analysis comparing SC and OFDM but with the difference of implementing DM systems was carried out. The performance of 50-Gbit/s DP-BPSK, 100-Gb/s DP-QPSK and 200-Gb/s DP-16-QAM is evaluated for single carrier and OFDM transmission. The same setup was employed having as a result a gross symbol rate of 31.5 Gbaud and 34 Gbaud for SC and OFDM respectively. Nonlinear mitigation techniques were applied because the interest of these simulations is to investigate the different pulse shapes and the advantages that can bring to long-haul optical communications.

Fig. 5.2 shows the maximum reach distance in a dispersion unmanaged link as a function of launch power for three studied modulation formats. A target BER of $10^{-2}$ was assumed, which is below the FEC limit of 20% overhead and soft decoding. Similar to the
results presented in Section 4.3, the pulse shape RZ50 reaches the longest distance for all modulation formats considered and the shortest corresponds to RRC with 0.3 of roll-off factor. The difference between the lowest and the highest values of distance is 1510 km for DP-BPSK, 707 km for DP-QPSK, and 233 km for DP-16-QAM, corresponding to an increase of the reach of 11.1%, 11.3% and 15.5% respectively. It can also be observed that the RRC and NRZ plots present similar results, meaning that adding a digital RRC does not have an advantage regarding the nonlinear tolerance, but as shown in [42] it is beneficial for increasing the spectral efficiency.

The results have shown that the maximum reach distance can be achieved by transmitting a RZ50 signal. For non-dispersion managed links the benefit using RZ50 was more evident reaching an improvement of the transmission distance of approximately 11% with respect to OFDM and the other pulse shapes. Regardless the lowest spectral efficiency of RZ50, it obtains the highest nonlinear tolerance.

5.5. Pulse shape comparison for SC with back-propagation

Keeping on with the investigations where the comparison between different pulse shapes for SC transmission systems were analyzed, in this section the nonlinear mitigation of SPM is hereafter considered. In this section, the comparison between two different pulse shapes (NRZ and RZ50) for single carrier, at a net data rate of 200-Gb/s employing a
5.5. Pulse shape comparison for SC with back-propagation

Figure 5.2.: Maximum reach distance versus launch power for 9 WDM channels transmission for a dispersion unmanaged link.
5. Non-dispersion-managed link

Figure 5.3.: Maximum reach distance versus launch power for a NRZ and RZ50 Single carrier transmission of 9 WDM channels

POLMUX-16QAM is reported. The signals are coherently detected with the nonlinear compensation scheme illustrated in Section 3.2. Both signals are generated at the transmitter at a net symbol rate of 25 Gbaud, an overhead of 20% is added for FEC and 5% for training symbol sequences, having as a result a gross symbol rate of 31.5 Gbaud for both cases. The scenario where the simulations are going to take place are several spans composed of a dispersion unmanaged optical link of SSMF fiber and EDFA with 6 dB of noise figure. As it is known, in a WDM system SPM is not the only effect which degrades the transmitted signal; the mitigation of inter-channel nonlinearities, particularly XPM represents a challenge for BP, as it requires the information of the co-propagating channels. After the analysis of the BP implementation, further simulations applying RFP in conjunction with BP will be reported within this chapter in order to show the efficiency of RFP in mitigating XPM.

Fig. 5.3 shows the comparison between the results with and without BP in terms of maximum reached distance as a function of launch power for NRZ and RZ50 pulse shaping. A target BER of $10^{-2}$ was assumed. For launch powers below -1 dBm, no improvement by employing BP can be seen since this is still within the linear region. A significant improvement is obtained when the optical launched power is higher than 0 dBm. A 11.9% of better performance is obtained at the optimal launch power, for the NRZ case. Similar to the NRZ results, RZ50 gains about of 15.8%. Besides increased maximum distance, both transmission pulse shapes reduce the SPM influence, shifting the optimal launch power from 0 dBm to 1 dBm as a result of the nonlinear mitigation scheme employed.
5.6. Joint work of back-propagation and RF pilot-tone for SC and OFDM

Since nonlinearities are becoming one of the limiting factor for long-haul transmission, in this section the joint usage of RFP and BP is proposed to mitigate the nonlinearities of a 200-Gb/s POLMUX 16-QAM SC and for OFDM system. The idea of the joint work of BP and RFP have not attracted the attention for SC systems so far, only few researches have been carried out using this idea. For this reason, we considered that would be interesting to analyze the performance of BP and RFP together in a SC system, in order to later compare it to the OFDM case [62, 61].

As it was explained in Section 3.1 the insertion of the pilot in our simulations is placed at the transmitter, with a specific offset respect to the central channel. The simulation setup implemented in this simulation is the same as in Fig. 5.4. The performance of a 200-Gb/s POLMUX-16QAM is evaluated for both modulation formats. At the receiver, the BP and RFP stages are applied in order to compensate for SPM and XPM respectively. It is important where and whether SPM and XPM compensation are located or used because system performance in the DSP could be degraded. In the case when nonlinear compensation is performed first with RFP and then BP, the XPM and partially SPM would be compensated by RFP and subsequently the remaining SPM should be compensated by BP. The result of this implementation would be a redundant SPM compensation as explained in [36]. For that reason and as shown in Fig. 5.4, BP is performed in our simulation analysis before the RFP technique, thus BP removes SPM from the signal and the pilot tone, and finally RFP compensates for the remaining XPM.

The obtained results for the aforementioned 200-Gb/s POLMUX-16QAM system are reported presenting one after the other, the performance of this system with and with-
out BP applying RFP and finally for the case where both techniques are simultaneously implemented. In the SC case only the NRZ pulse shape was considered. The comparison between four different mitigation schemes are presented in terms of maximum reachable distance as a function of launch power for NRZ pulse shaping where the target BER assumed in our system is still $10^{-2}$. As reported in the results of last section, no significant improvement can be seen for power values below -1 dBm since the signal is only ASE-noise limited. For launched power values higher than 0 dBm the signal experiences the effects of nonlinearities and the three compensation schemes mentioned before show different tolerance against them. Compared to the case where no compensation is applied, all techniques provide a clear benefit. Directly from Fig. 5.5(a) where NRZ results are displayed, we can draw the following conclusions: the compensation provided by single RFP is less performing than the one obtained by using a standard BP module. Moreover, the joint use of BP and RFP mitigation provide the absolute best performance, and the maximum improvement achieved is of about 18% compared to the NRZ case where nonlinear compensation was not implemented. On the other hand, in Fig. 5.5(b) the results where OFDM is transmitted are shown. The results with BP show an improvement of 2%, similar than the only usage of RFP which is 1%. In both cases the improvement is less than for the case of SC. However, the combination of BP and RFP provides an improvement, at the optimal launch power of 13%, more than applying only BP or RFP separately, which means that XPM is efficiently compensated and both techniques must be implemented together in order to push the OFDM performance to a value comparable to the NRZ where no nonlinear mitigation techniques are applied.
5.6. Joint work of back-propagation and RF pilot-tone for SC and OFDM

Figure 5.5.: Maximum reach distance versus launch power for 9 WDM channels POLMUX 16-QAM transmission with nonlinear mitigation in a NDM scenario
6. Conclusion

In this thesis, the comparison between the SC and OFDM modulation formats have been investigated. Several scenarios and simulation setups have helped us to support all the analysis shown in this work. The nonlinear mitigation technique has also been considered as an important issue because better signal performance can be achieved, reducing the effects of nonlinearities. With or without nonlinear mitigation single carrier has always reported the best result in all the considered scenarios compared to the OFDM results. The comparison between SC and OFDM was at the beginning primarily focused on the scenarios where nonlinear effects were not compensated for. First of all the comparisons of different pulse shapes and OFDM with different modulation formats were carried out. The results reported that in the case where a DM is employed, OFDM performed the worst in every situation. The best performance was obtained for SC when RZ50 pulse shaping was transmitted. In fact, as we explained in this thesis that employing a RZ50 gives you the advantage of having a high quality NRZ pulse due to the optical filtering at the transmitter. On the other hand, when comparing both modulations formats in a NDM scenario OFDM reached the same performance as the worst RRC roll-off factor, giving a difference between the OFDM and the RZ50 performance of 15.5% when a DP-16-QAM was transmitted.

After looking at different systems performance where the most limiting factor was defined as the nonlinear effects, the two most popular nonlinear mitigation techniques were employed, which are: BP and RFP. Both techniques show more efficient mitigation when NDM scenario was considered due to the fact that in DM nonlinear effects dramatically increase their importance as it increases XPM making it more challenging for the overall compensation. After demonstrating that BP and RFP can really compensate for SPM and XPM effects respectively, we proposed the idea of the joint usage of both techniques in order to compare the performance of SC and OFDM when the nonlinear effects could be considered a limiting factor any more. In that case, where BP and RFP where applied together in a NDM scenario we showed an improvement of 18% and 13% to SC and OFDM respectively. These improvements where referred to the cases where no nonlinear mitigation was applied to the signal. However when we analyzed the DM links the results showed how complicate is to compensate for the different nonlinear impairments
6. Conclusion

and thus, lower improvement was obtained. After analyzing all the results obtained in all the investigations presented in this thesis certain results can summarized. SC has always reported a better performance than OFDM concluding that SC is better than OFDM for the cases considered in this work. Furthermore, the usage of nonlinear mitigation techniques concluded that the joint work of BP and RFP could lead into an important advantage for long-haul optical communication systems.
### A. List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BP</td>
<td>Back-Propagation</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase-Shift Keying</td>
</tr>
<tr>
<td>CD</td>
<td>Chromatic Dispersion</td>
</tr>
<tr>
<td>CO-OFDM</td>
<td>Coherent Detection Optical Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>CPE</td>
<td>Common Phase Error</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-analog Converter</td>
</tr>
<tr>
<td>DBPSK</td>
<td>Differential Binary Phase Shift Keying</td>
</tr>
<tr>
<td>DCF</td>
<td>Dispersion Compensating Fibers</td>
</tr>
<tr>
<td>DM</td>
<td>Dispersion Management</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>DPSK</td>
<td>Differential Phase Shift Keying</td>
</tr>
<tr>
<td>DQPSK</td>
<td>Differential Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>EAM</td>
<td>Electroabsorption Modulators</td>
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<tr>
<td>EDC</td>
<td>Electronic Dispersion Compensation</td>
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<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
</tr>
<tr>
<td>FDE</td>
<td>Frequency Domain Equalizer</td>
</tr>
<tr>
<td>FDM</td>
<td>Forward Domain Multiplexing</td>
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<tr>
<td>FEC</td>
<td>Forward Error Correction</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency-shift Keying</td>
</tr>
<tr>
<td>FWM</td>
<td>Four Wave Mixing</td>
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<tr>
<td>GVD</td>
<td>Group-Velocity Dispersion</td>
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<tr>
<td>ICI</td>
<td>Inter-Carrier Interference</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverted Fast Fourier Transform</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter-Symbol-Interference</td>
</tr>
<tr>
<td>LEAF</td>
<td>Large Effective Area Fiber</td>
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<tr>
<td>LO</td>
<td>Local Oscillator</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<td>---------</td>
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<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple Output</td>
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<tr>
<td>MZM</td>
<td>Mach-Zehnder-Modulator</td>
</tr>
<tr>
<td>NF</td>
<td>Noise Figure</td>
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<tr>
<td>NLSE</td>
<td>Nonlinear Schrödinger Equation</td>
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<tr>
<td>NRZ</td>
<td>Nonreturn-to-zero</td>
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<tr>
<td>OADM</td>
<td>Optical add/drop multiplexers</td>
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<tr>
<td>OCS</td>
<td>Optical Communication System</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Domain Modulation</td>
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<tr>
<td>OOK</td>
<td>On-Off Keying</td>
</tr>
<tr>
<td>OSNR</td>
<td>Optical Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase-Shift Keying</td>
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<tr>
<td>PAPR</td>
<td>Peak-to-Average Power Ratio</td>
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<tr>
<td>PLL</td>
<td>Phase-locked Loop</td>
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<tr>
<td>PMD</td>
<td>Polarization Mode Dispersion</td>
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<tr>
<td>POLMUX</td>
<td>Polarization-Multiplexed</td>
</tr>
<tr>
<td>PSR</td>
<td>Pilot-to-Signal Ratio</td>
</tr>
<tr>
<td>RFP</td>
<td>Radio Frequency Pilot</td>
</tr>
<tr>
<td>ROADM</td>
<td>Reconfigurable Optical add/drop Multiplexers</td>
</tr>
<tr>
<td>RZ</td>
<td>Return-to-Zero</td>
</tr>
<tr>
<td>SC</td>
<td>Single Carrier</td>
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<tr>
<td>SC-FDE</td>
<td>Single Carrier with Frequency Domain Equalization</td>
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<tr>
<td>SPM</td>
<td>Self-Phase Modulation</td>
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<tr>
<td>SSFM</td>
<td>Split Step Fourier Method</td>
</tr>
<tr>
<td>SSMF</td>
<td>Standard Single Mode Fiber</td>
</tr>
<tr>
<td>TDE</td>
<td>Time Domain Equalizer</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross Phase Modulation</td>
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</tbody>
</table>
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