POLITECNICO DI TORINO

Master degree course in Electronic Engineering

Master's Degree Thesis

Analysis of Multi-Carrier Modulation Techniques for Optical Communication Systems

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Lorenzo

Summary

The main goal in the development of telecommunication systems is to meet a continuously growing data demand. Research is focused on finding new solutions for more flexible networks able to sustain high data rates maintaining a good quality of the transmitted signal.
In the area of optical networks,the introduction of the Wavelength Division Multiplexing (WDM) and, in particular, of the Reconfigurable Add-Drop Multiplexers (ROADMs) in network nodes, made possible the implementation of the dynamic wavelength routing. As a drawback, the introduction this flexibility also introduced distortions due to the filtering effect caused by cascading several ROADMs along the optical channel path. This is becoming more and more relevant so a detailed study is necessary in order to find a good solution for reliable transmissions. The transmitted signal, passing through several ROADMs, is filtered with the consequent narrowing on the edges of the signal spectrum. A solution proposed recently is based on the used of multi-subcarrier transmission with the optimization of the modulation format and of the allocated power applied to each subcarrier: Frequency Division Hybrid Modulation Format(FDHMF).
In this work, we have analyzed, using analytical and simulative tools, several scenarios considering different bit rates, symbol rates and modulation formats.The main novelty of this study with respect to previous work is the analysis of a realistic model for ROADMs taking into account a tuning uncertainty: the central frequency of the ROADMs is considered as a random variable. We have shown the existence of a unique relationship between the overall transfer function properties (central frequency and -3 dB bandwidth) and system penalty.
Based on this, we propose a method for the automatic monitoring of performance to be applied in practical receiver in real-time.

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Motivation

The actual scenario in the telecommunication world is evolving continuously, and starting from the creation of the Internet and then the World Wide Web in 1993 the data traffic sees a continuous growth. In 2002, for the first time network data traffic became higher than the voice data traffic and today this trend is going on because services are moving to digital. The future of telecommunication sees an high demand of data traffic following the trend to move toward Internet of Things and 5G technologies. All the sectors of the society needs higher bandwidth requirements. Home users will move toward speed requirements of Gigabits per second with the advent of high definition broadcast services. This technological revolution needs to be sustained by an high capacity network with the possibility for companies to upgrade the system. Starting from the invention of the laser and the subsequent introduction of optical fibers as medium in 1970, there has been a run to obtain higher capacity systems. In the last two decades of 20^{th} century, the advent of optical amplifiers with the economic apllication of WDM and reconfigurable networks permitted to telecommunication companies a continuous upgrade of networks. From the state-of-the-art, the optical communications field saw an exponential growth and also today this trend is in a continuous evolution. The goal of companies and researchers is not only to meet the actual data traffic demand but is also to think in perspective of offering a suitable network structure given the rapid pace of development of modern technologies. In this scenario, optical communications play an important role, constituing the basis to enable future technologies. Today, it is impossible to think about a tech device without data exchanges and bandwidth requirments. The described scenario was the spark that brought my interest to fiber optical communication systems which, although they are not visible daily, constitute a vital part of everyday life.

Organization of the thesis

The work was carried out in MATLAB environment using the OptDSP library [1]. The aim is to simulate the behaviour of communication systems, configuring transmitter-receiver chain and channel's charateristics as well.
The thesis is organized in two main parts divided in 4 chapters. The first part, composed by two chapters, contains the theoretical background and basic principles on which the studied system is based. In particular, Chapter 1 contains concepts of communications system with a focus on the optical field, Chapter 2 presents a description and basic principles of the system analyzed in the thesis. The second part presents simulation results in Chapter 3 and final conclusions in Chapter 4.

Chapter 1

Communication systems

A communication system provides an interconnection between a transmitter and a receiver in order to exchange information through a channel. The general structure of a communication system is composed of three components: the transmitter, the receiver and the channel as shown in figure1.1

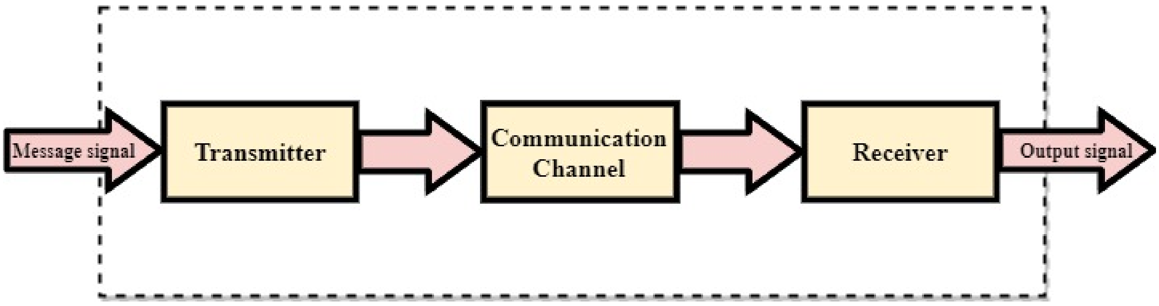

Figure 1.1: *General block scheme of a communication system.*

There are two main families of communication systems depending on the channel: wireless and wired. A radio system is included in wireless communication systems while all other systems, where the channel is physically present(twisted pair or optic fiber), are wired. The function of the transmitter is to modulate the signal so that it is suitable to be transmitted over the channel.
The role of the channel is to provide a path between the transmitter and the receiver. The signal arrives then to the receiver and it has the function to recover the original message applying the demodulation. In theory, the sent and the received messages should be the same but in real systems the information is affected by interference.
The modulation modifies the signal, and depending on the information signal, a

carrier wave changes and the result is a modulated signal that will match the bandwidth of the channel. The modulation also permits the multiplexing, for which different signals can be transmitted on the same channel simultaneously.
The modulation transforms the digital information into an analog signal that is received with an additive noise introduced by the channel.
A communication system is not only composed of transmitter and receiver but, in the case of more than two users, we need other elements like nodes and links for managing the data traffic. The communication system can be simple, as shown in figure 1.1 , or can be inserted in a more complex network with thousands of users, nodes and links with different configurations; networks charactheristics will be further explained in more depth in the following sections.

1.1 Topologies

The elements of a network can be organized in differnet ways called topologies. Each node can have one or more connections with the devices of the network. We can describe each topology graphically depending on how nodes and devices are linked. The most common topologies are shown in figure 1.2.
Point-to-point topology is the simplest one where two end-points are directly connected by a link.
Ring topology is a closed configuration; data move inside the ring in a single direction from one node to the next one to reach the final destination.
In star topology there is a central node(hub) that is point-to-point connected with several users. Data traffic passes through the central node that is a repeater or a switch while peripheral nodes are clients.
A mesh network does not have a hierarchical topology, the network is flexible and it can reconfigure in case of faults. A mesh network can be fully or partially connected. In the first case each node is connected with all the other nodes while in the second case a node can be connected to one or more nodes. The advantage of mesh networks is the redundancy of paths and so communication is possible even if some paths are out of service. Nowadays networks for long-haul communication systems are mostly configured with a mesh topology because of better reliability and the possibility to exploit nodes as switches to implement wavelength routing.

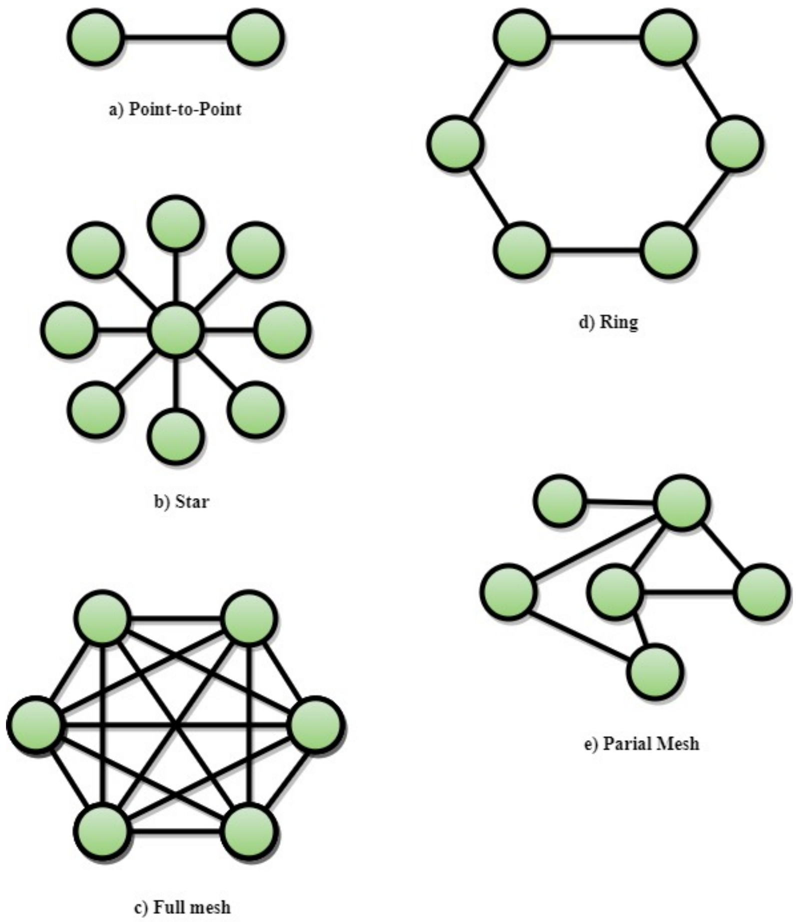

Figure 1.2: *Network topologies.*

1.2 Optical communication systems

The idea to transmit information using light started many centuries ago when people tried to communicate through lamps or similar devices. Using light for communication purposes was developed in the eighteenth century with systems that we can call "optical telegraphs".
The nineteenth century saw the development of electrical communication systems and then microwave systems. The increase of bit rate for communications and the high losses of coaxial cabling highlighted main limitations of these systems because of the need of a huge number of repeaters and the impossibility to increase the bit rate. The first step towards optical communications was the invention of lasers and their use in optical communications. The second milestone in optical communication systems was finding a suitable way to guide the light: optical fibers.

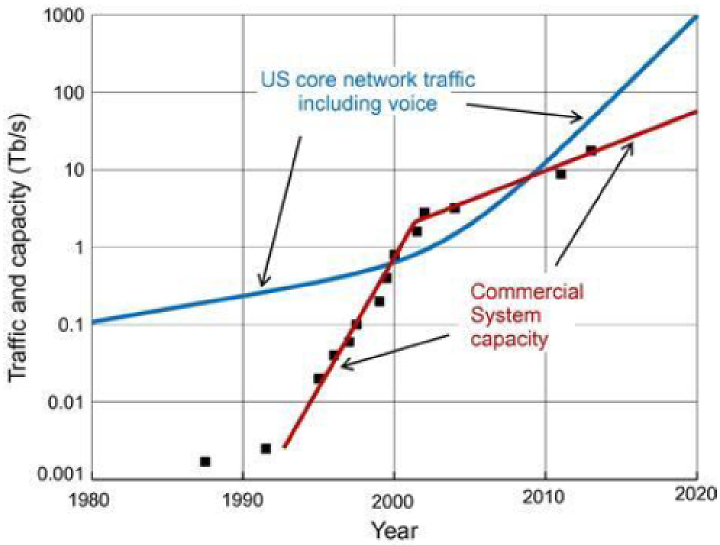

Figure 1.3: *Commercial system capacities (squares and red curve) and total network traffic including voice (blue curve).[[4]]*

From 1975, the main focus of research was into reducing loss in fiber optics. The main difference between an optical communication system and previous systems is the frequency range of carrier waves. Optical communication systems can be mainly divided into guided and unguided systems. While unguided systems spread the optical beam in space, guided ones confine the optical beam within an optical fiber. The focus of this thesis is on guided systems, more commonly defined as fiber-optic communication systems. Nowadays optical fiber communications are very widespread mostly for telecommunications applications and in particular for long haul systems where high capacity and low losses can be better exploited.

1.2.1 Optical fibers

Fiber Optics technology is based on flexible waveguides for light. The core of this technology is the fiber. The structure of the optical fiber is based on a coaxial cable made up of one or more optical fibers.
The inner part of the optical fiber cable is occupied by the optical fiber. It could be made of plastic materials or glass(silica). The core is fragile and it is surrounded by protective polymeric cladding to protect the fiber from external stress like bending. This structure gives us a robust and elastic fiber optic cable. The external layer is the jacket and its material depends on the fiber application. The color of the jacket indicates the properties of the fiber.

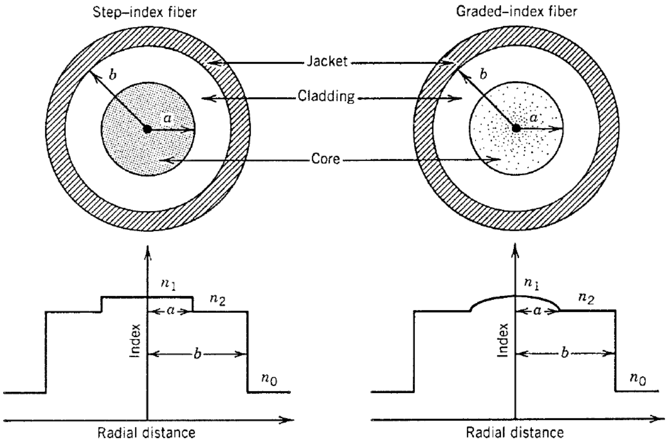

Figure 1.4: *Cross section and refractive-index profile for step-index and graded-index fibers.[2]*

The principle behind optical fibers works on total internal reflection that allows fibers to be used as a guide for the light. The use of glass fibers became possible when combined with cladding resulting in a drastic drop in losses to approximately 0.2 dB/Km near 1.55 μm spectral region for Standard Single Mode Filber(SSMF). The first important characteristic is the material used for the core and the cladding. The reflection of the light depends on the refractive indices of the core and the cladding and the difference at their interface. The refractive index of cladding is lower than that of the silica glass core. If at the core-cladding interface the index changes abruptly the fiber is called step-index while if the core index decreases gradually the fiber is called graded-index fiber [2].
Another important classification is between single mode and multi mode fibers.
A single mode fiber is characterized by a small core size about 10 μm that permits only one mode or ray of light to be transmitted typically with a wavelength of 1310 or 1550 nm. For this reason, there is little light reflection created when light passes through the single mode fiber core. This will lower the fiber attenuation and make it possible for the signal to travel further. Thus single mode fibers are usually used in long distance and higher bandwidth applications.
Multi-mode fibers have larger cores (62.5 µm or 50 µm) that guide many modes simultaneously, which means that more data can pass through the multi-mode fiber core at a given time. This will create more light reflections and a higher dispersion and attenuation rate reducing the quality of the signal over long distances. Generally, multimode fibers are used over short distances and for data and audio/video applications in Local Area Networks(LANs).

For long-haul telecommunication applications silica single mode fibers at 1550 nm are used. One important feature of fiber optic systems is linked to the loss due to the particular fiber material and the wavelength the system is operating on. There are three main windows. The first window at 800-900 nm is called "original" because it was the first used but has high losses and fiber amplifiers have not been developed to sustain this window. It is used only for very short distances.
In the second window, around 1300 nm, the losses are lower for silica fiber. This window is used for long-haul transmission but it is not as good as the third window at around 1500 nm. The third window utilizes wavelengths around 1500 nm. Here erbium-doped fiber amplifiers offer high performance but unusual dispersion phenomena can occur. The second and third windows are subdivided into bands as shown in figure 1.5.

	Optical band	Wavelengths
O	(Original)-Band	1260 nm – 1360 nm
E	(Extended)-Band	1360 nm – 1460 nm
S	(Short)-Band	1460 nm – 1530 nm
C	(Conventional)-Band	1530 nm – 1565 nm
L	(Long)-Band	1565 nm – 1625 nm
U	(Ultralong)-Band	1625 nm – 1675 nm

Figure 1.5: *Wavelength Bands. [3]*

In the case of silica optical fiber there are two main wavelength windows where losses are lower than 0.5 dB/Km. For wavelengths around 1.5 nm, as shown in figure 1.6 losses are 0.2 dB/Km.This lower value justifies the huge use of silica in the production of optic fiber.

1.2.2 Amplifiers

The need of using long-haul systems is to reach long distances. The most important obstacle is the fiber attenuation that is very low in the C band with a value of 0.2 dB/Km.

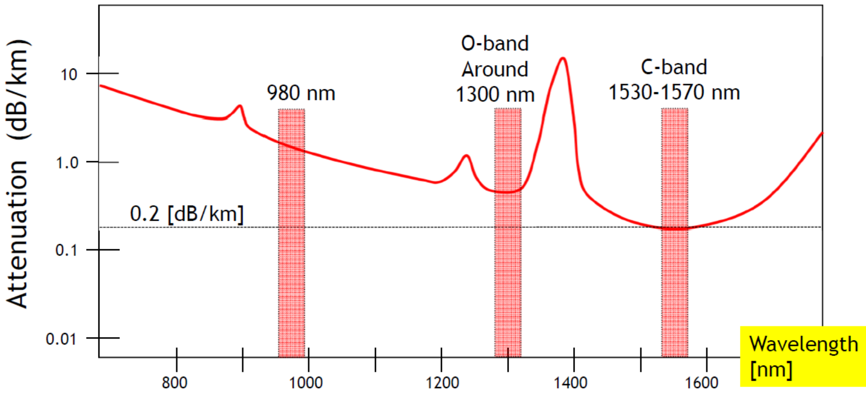

Figure 1.6: *Fiber attenuation.*

In the early systems there was an amplification system made of a receiver/transmitter pair with an optical-to-electrical-to-optical conversion of the signal. The introduction of optical amplifiers permits to amplify the signal in the optical domain, without moving to the electrical one. The problem of attenuation is solved with single mode silica that have an attenuation of 0.2 dB/Km.
Other impairments, such as the Kerr effect, a nonlinear effect causing the increase of the refractive index and self-phase modulation, limit the amount of the transmitted optical power. For this reason, exploiting and improving amplification schemes is fundamental. In particular, the C band, corresponding to wavelengths around 1550 nm, is the selected band for long-haul transmissions for several reasons. In fact, in that window, for the SMF fiber, nonlinear effects are small, fiber attenuation is 0.2 dB/km and EDFAs have the best amplification performances. In nowadays systems we can find different types of optical amplifiers and different configurations of amplified optical systems. There are three main congigurations:

- Single span non amplified
- Single span amplified
- Multi span amplified

In the single span amplified system, there is an optical amplifier at the receiver input acting as an optical pre-amplifier. In this configuration there are two noise sources: electrical amplifier and optical pre-amplifier. A high gain in the pre-amplifier guarantees the electrical amplifier to be negligible with respect to the Amplified Spontaneous Emission (ASE) noise, the main noise source. The ASE noise is Gaussian, white and additive on the optical field.
There are three main types of optical amplifiers:

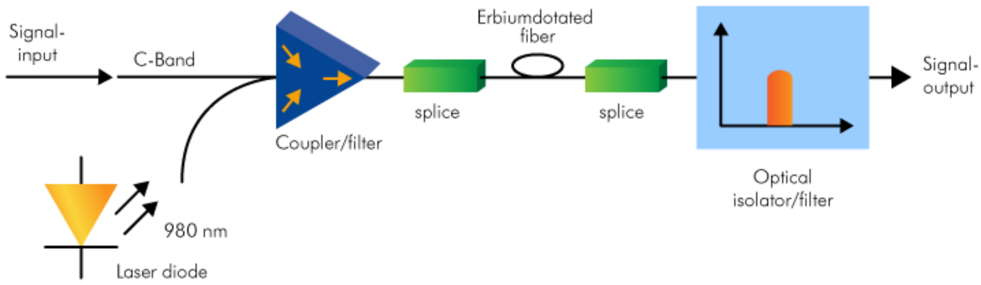

Figure 1.7: *Configuration of an Erbium Doped Fiber Amplifier [[5]]*

- Erbium Doped FiberAamplifiers(EDFA): is a short span of doped fiber that amplifies light instead of attenuating thanks to the Erbium ions. When Erbium ions are illuminated with a light at a specific wavelength around 980 nm or 1480 nm it is excited to an high energy state. They will decay when they encounter emitting ligth within 1525 nm and 1565 nm with the resulting signal amplification.

- Semiconductor Optical Amplifiers(SOA) use the semiconductor as gain medium in order to increase optical launch power to compensate for the loss of the fiber. SOA acts between 850 and 1600 nm. The working principle is the same of a semiconductor laser without feedback. A SOA amplifies incident light through stimulated emission. The light travels through the active region and electrons lose energy in photons that have the same wavelength of the optical signal. With the spread of EDFAs the use of SOAs is now negligible because performances are not comparable with EDFA.

- Raman amplifiers based on Raman scattering induced by the interaction between the structure of the medium and the incoming photon. The medium has the characteristic to oscillate at different energy levels. Molecules, when excited, can jump to an energy level higher than the initial one. When in the spectral bandwidth where the Raman Scattering takes place there is also a flow of photons, the energy is transferred from the pump photons to the propagated flow of photons. These principles are the basis of the Raman amplifiers with a distributed amplification.

The in-line optical amplified link shown in figure 1.8 is the configuration of interest for the thesis with the addition of ROADM modules as explained in the next section.

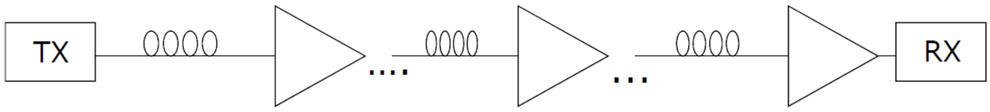

Figure 1.8: *In-line optical amplifiers configuration.*

1.2.3 WDM, ROADMs and WSSs

The development of modern optical communications systems is based on Wavelength Division Multiplexing(WDM) and EDFA that together permit to reduce costs and increase the system capacity. Thanks to WDM we can multiplex, in the frequency domain, more optical carriers modulated by using indipendent electrical bit streams in the frequency domain [2].

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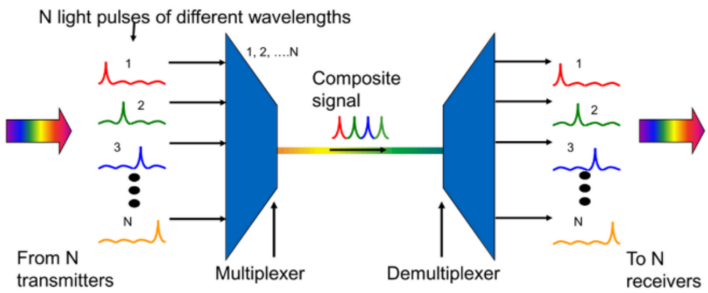


Figure 1.9: *Wavelength Division Multiplexing. [7]*

WDM allows to increase the capacity of a system thanks to the simultaneous transmission of the multiplexed carriers on the same fiber. This means that there is also an advantage in terms of costs but also in flexibility. At the receiver side a demultiplexer allows to select the proper frequency, recovering the original optical carriers. Main advantages for companies is that this flexibility, extended also for amplifiers, permits to improve technology and performances of a network without changing the backbone network.

In actual scenarios there is the necessity to connect a huge number of users and to sustain an increasing data traffic demand. Referring to long-haul systems covering large areas, WDM is exploited in mixed topology networks generally considered as mesh network. Nodes of the network are configured as switches implementing an all-optical network that permits to a signal to travel through several nodes trasparently. The introduction of Reconfigurable Add Drop Multiplexers(ROADMs) enabled the possibility to apply a wavelength-based routing, this permitted to manage

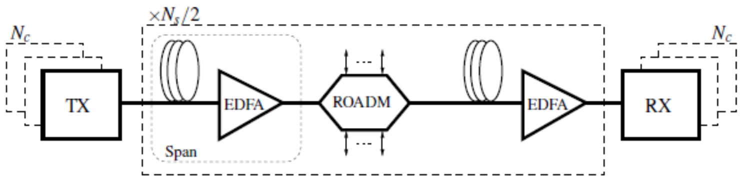


Figure 1.10: *Multi-span amplified link with ROADM. [6]*

the data traffic through the huge number of nodes and users. At each transparent node the WDM signal has the possibility to be changed adding or dropping channels. Figure 1.10 shows the general configuration of an optical link made of several spans (Ns/2, where Ns is the number of spans). In particular, at the end of the link, there is a ROADM with the ability of choosing the desired optical path(associated to a specific wavelength). The selection of the wavelength is enabled by two Wavelength Selective Switches(WSSs), one at the input and one at the output of the ROADM. The advantage is the possibility to add or drop multiple wavelengths carrying data channels without the need to apply an optical-electric conversion. As shown in figure 1.11 ROADMs are placed in network's nodes and they include not only the switching core but also controllers,optical amplifiers and other components.

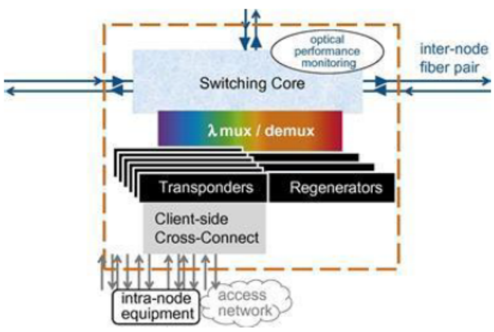


Figure 1.11: *Structure of a ROADM. [4]*

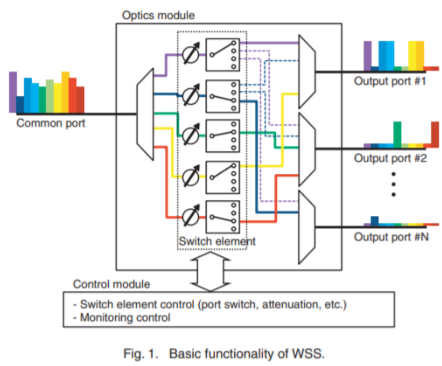


Figure 1.12: *Basic functionality of WSS. [8]*

The main component of a ROADM is the switching core, where wavelength switching is performed. In today's ROADMs the core is an N-degree wavelength-selective switch enabling the possibility to connect a node with several output fibers with the possibility to apply an in-service upgrade.

Chapter 2

The coherent optical system

The system considered in this thesis is an amplified system with a multi span configuration, where ROADMs are placed between links as nodes. The topology could be considered as a meshed one where the signal travels through ROADMs and it is amplified through the EDFA technology.
Optical fiber sustains two independent and orthogonal optical signals on two polarizations ,which electrical field is described in formula 2.1. Each of them is a complex signal identified with a real and an imagianry part which can be represented on a complex plane as shown in figure 2.1.

$$\vec{E} = \left[E_{Ix}(t) + jE_{Qx}\right]\hat{x} + \left[E_{Iy}(t) + jE_{Qy}\right]\hat{y} \tag{2.1}$$

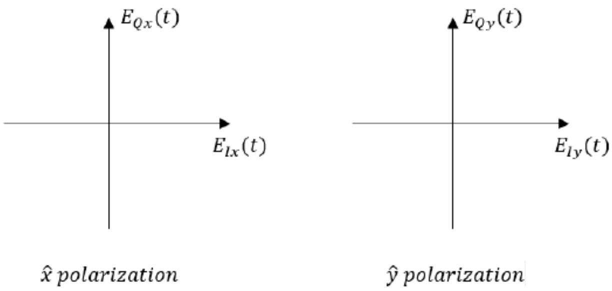


Figure 2.1: *Electric field components.*

The signal is composed of four components having four degrees of freedom. It is possible to use a polarization multiplexing that permits us to transmitt two signals on the two polarizations. It is also possible to increase the number of bits per pulse so that we obtain more complex constellations increasing the capacity. The simplest modulation format is On-Off Keying(OOK), where a binary one is represented by the presence of a carrier while the absence of a carrier represents a binary zero. Another modulation is Phase-shift-keying(PSK) where digital data are modulated by changing the phase of a constant frequency carrier wave. In Quadrature Phase Shift Keying(QPSK), two bits are transmitted to represent four different phases depending on the combination of the couple of bits. QPSK doubles the capacity of OOK. Moving to more complex modulations exploiting polarization multiplexing there are 2^N Quadrature Amplitude Modulation(QAM) formats where N is the number of transmitted bits per pulse. Number of bits per pulse increases for more complex modulation formats increasing the capacity. If on a side the capacity increases, on the other hand there is also an higher complexity of the transmitter and receiver. In order to exploit at maximum the four degrees of fredoom the modulator structure at the transmitter is composed by four more simple modulators.

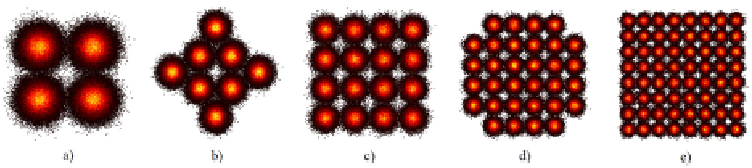


Figure 2.2: *Main QAM modulation formats: a)QPSK b)8-QAM c)16-QAM d)32-QAM e) 64-QAM. [9]*

At the receiver all the four components must be extracted with a coherent receiver where a local oscillator is used(figure 2.3). The local oscillator is aligned with the desired component and set to the same frequency. Since it is not guaranteed that the phase coincides with the transmitter's one, an electrical Digital Signal Processing(DSP) is applied to re-align the axes and decode the signal in the proper way.
At the coherent receiver the signal is affected by Amplified Spontaneous Emission (ASE) noise due to the Erbium Doped Fiber Amplifier and other distorions introduced by the filtering effects of the ROADMs. In both in-phase and quadrature components noise is locally white so that a matched filter may be used.

2.1 Wavelength Selective Switches

The Wavelength Selective Switch is the core of ROADMs. The main feature is the ability to route or block a wavelength. As previously written, the WSS has an input port and several output ports where whavelengths are swithced. The advantage in

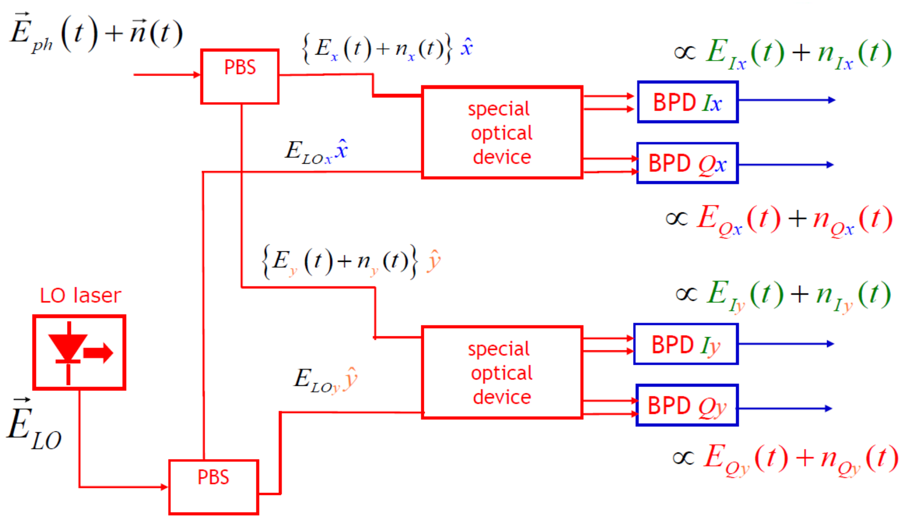


Figure 2.3: *Coherent receiver front end.*

using a WSS is the dynamic reconfiguration.
What is interesting for the purpose of the thesis is the behaviour of the WSS described by its transfer function represented by the formula 2.2 where B is the bandwidth of the frequency window where the WSS is placed and N_{WSS} is the number of cascaded WSS. From an analytical point a view, a WSS can be seen as a bandapass filter with the power spectrum represented by a rectangular aperture. The output optical amplitude is the result of the convolution between the aperture function and the optical transfer function(OTF) with standard deviation $\sigma = BW_{OTF}/(2\sqrt{2ln2})$ [12] where the BW_{OTF} is the 3 dB bandwith.

$$S(f) = \left[\frac{\sigma\sqrt{2\pi}}{2} \left[\text{erf}\left(\frac{B/2 - f}{\sqrt{2}\sigma} \right) - \text{erf}\left(\frac{-B/2 - f}{\sqrt{2}\sigma} \right) \right] \right]^{N_{WSS}} \tag{2.2}$$

The result of a casacade of WSS is that the increase of N_{WSS} reduces the bandwith narrowing the transfer function, leading to stronger filtering effects on the singal. Assuming that cascaded WSSs are ideal and identical, it is easy to predict the final bandwidth. The optical spectrum of N_{WSS} cascaded WSS is the seen function raised to N_{WSS}. A qualitative example of the resulting transfer function for an increasing number of cascaded WSSs is shown in figure 2.4.
In the tested optical system the WSS is configured in two different ways depending on the sustained symbol rate, whose values are summarized in table 2.1.
The study of the behaviour of the system depending on the number of WSSs will

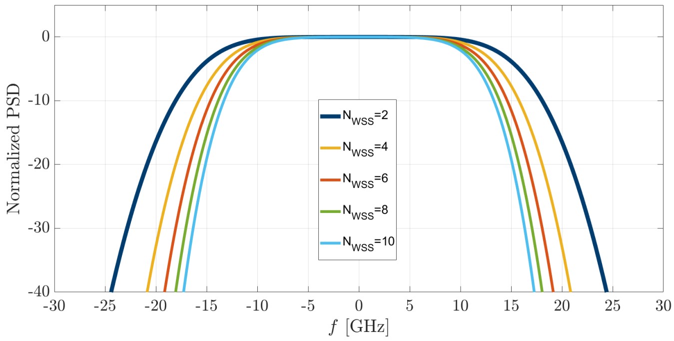


Figure 2.4: *WSS transfer function for different numbers of cascaded devices with* $B = 37.5GHz\ and B_{OTF} = 10.4GHz$.

be a key point. Indeed, the resulting filtering effects introduce Inter-Symbol Interference (ISI) and Signal-to-Noise Ratio(SNR) losses.

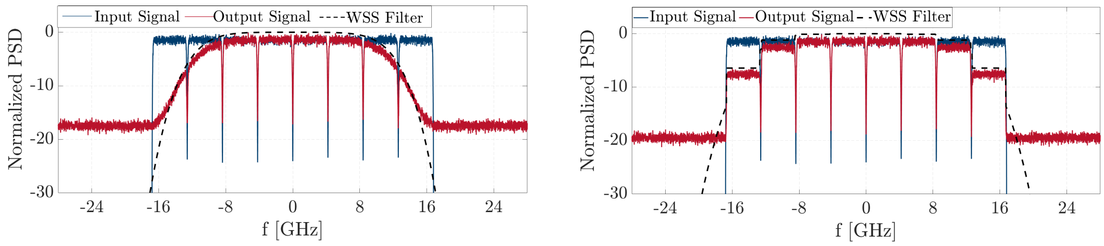
	32 GBaud	**64 GBaud**
B	37.5 GHz	75 GHz
B_{OTF}	10.4 GHz	10.4 GHz

Table 2.1: *WSS bandwidth.*

The WSS modelled by the formula 2.2 behave as a real filter but it could be applied also in an approximated version. In the apprximated filter, the WSS transfer function is calulated for each subcarrier taking,within the subcarrier bandwidth, the average value of the WSS transfer function considering the average loss. This approximation of WSS filter is considered as theoretical and so results are considered as theory. The analytical expression (2.2) is used in the time-domain simulations of the system where the SNR is taken from averaging the SNRs of each subcarrier as shown in figure 2.5.

2.2 Forward Error Correction

Forward error Correction is a technique to encode the original message consisting in the insertion of redundant bits designed by a FEC algorithm scheme. At the receiver the message is decoded and this affords the possibility to correct errors. When the FEC is applied, the original message is encoded so that the sequence of n bits is encoded in a longer codeword of k bits. The raw bit rate increases and this means a decrease in the symbol rate caused by the Over Head(OH). The Over Head



a) Real *b) Discretized*

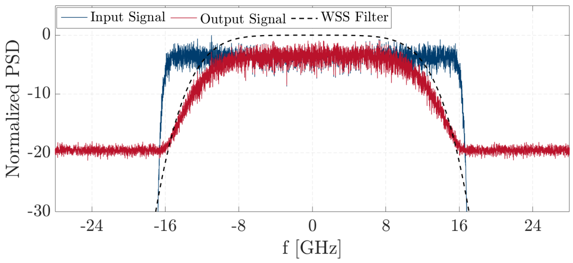
Figure 2.5: *Attenuation of the ROADM transfer function in real(a) and discretized(b) case.*

is the ratio between the added redundant bits and the length of the codeword. The FEC technique can be classified in: Soft-Decision FEC and Hard-Decision FEC that differ for OH with a value in a range of 7-20% [13]. The difference is that in HD-FEC the decoding is based on hard-bits and bits are defined with only two levels: "0" or "1". Soft-Decision decoding is based on soft levels where actually the decision is made on a symbol-basis, not on a bit-basis. If the FEC decreases the net symbol rate, on the other hand it improves performances, in particular when high order formats are used, which are more sensitive to channel impairments.
In this thesis a Hard Decision FEC is applied with 28% OH. The FEC is the same for all subcarriers in the case of multi subcarrier system.

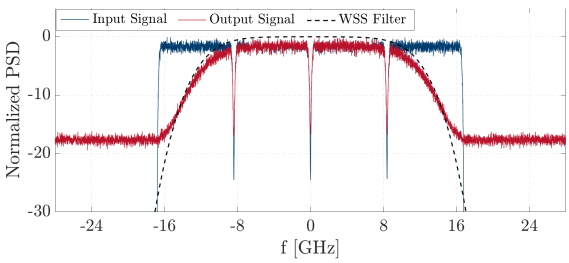
2.3 Single and multi-subcarrier systems

The optical communication systems have been improved in the years in order to obtain better performances and to increase capacity and flexibility. In fact, the goal is to sustain the increase of the data rate demand. If the inital systems were based on a single carrier transmission, in order to increase capacity multi-subcarrier(MSC) modulation was introduced.

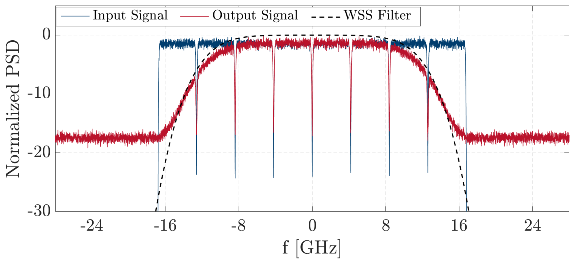
The increase of capacity network in a single carrier system is possible using higher order modulation formats of the type 2^N-QAM with N bits per symbol. The increasing of symbol-rate is more limited with the use of the bit-rate flexibility in single carrier transceivers [9].
Another important limitation is posed by the filtering effects introduced by WSS, we can see how the output signal is penalized at the bandwidth edges because of the narrower transfer function when more WSS are in cascade.



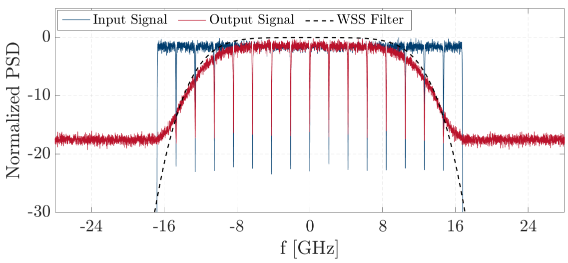
a) 1 subcarrier



b) 4 subcarriers



c) 8 subcarriers



d) 16 subcarriers

Figure 2.6: *Effects of 8 cascaded ROADMs on the spectrum of a 16-QAM signal with symbol rate of 32 GBaud for different number of subcarriers.*

To avoid these limitation another strategy is introduced: multi-subcarrier modulation. Within this paradigm different solutions are proposed. In coherent optical communications, orthogonal frequency-division multiplexing(OFDM) has been used but with different limitations. The high peak-to-average power ratio brings non linear interferences during signal propagation and stringent requirements in DAC and ADC conversion. The other multi-subcarrier solution is the electronic subcarrier multiplexing(SCM). This technique has been deeply invesitgated because of better performances against non linear effects. The SCM signal is composed by N_{SC} subcarriers with a symbol rate N_{SC} times lower respect the overall one. This appraoch permits to increase the spectral efficiency assigning different modulation format to each subcarrier exploiting the concept of frequency-domain hybrid modulation formats(FDHMF) as proved in [9].
With FDHMF the system has a higher tolerance to filtering effects of ROADMs taking advantage of the symbol rate optimization. The advantage from the use of a large number of subcarriers is that the increased granularity permits to decrease filtering effects caused by ROADMs. Another possibility against filtering effects is to use low-order QAM modulation formats at the edges of the bandwidth which are more resilient to filtering.[9]

2.3.1 Optimization strategies for multi-subcarrier transmission

Multi-subcarrier transmission offers more flexibility to reach better performances. As presented in [10] and [11], better performances can be obtained optimizing the per-subcarrier power, modulation format or both.
Power allocation became relevant when a multi-subcarrier approach is used. There are different power allocation strategies starting from the Same Power strategy arriving to Bit and Power Loading Strategy. With Same Power approach all subcarriers have the same amount of power and so power ratios are zero. Water filling strategy takes into account the SNR for power allocation, subcarriers with higher SNR have higher power. Power Loading strategy optimizes power allocation of each subcarrier but it does not modify modulation format.
Other strategies are the Minimum BER where the optimum SNR is found in order to minimize the SNR for each subcarrier and Bit Loading strategy where modulation formats are optimized maintaining the same power.
A very powerful strategy is Bit and Power Loading, which strategy finds the optimum modulation format and so optimizes power ratios for each subcarrier.
Some of these strategies have been applied in the thesis in order to find the optimum performance highlighting the advantages with respect to the cases when these strategies are not applied.

2.4 Performance evaluation metrics

At the receiver side, in particular, referring to this work, there are filtering effects and link attenuations which are evaluated observing some parameter:

- The Signal to Noise Ratio(SNR) is the more used parameter defined as the ratio between the signal power and the noise power over a defined bandwidth.

- Bit Error Rate(BER) is the ratio between the number of wrong received bits and total transmitted bits. This is one of the most used parameter.

- Power Ratio(PR) is a measure that is interesting in the multi- subcarrier transmissions where total available power is divided in varying amount among subcarriers. It is defined as the ratio between the power of a subcarrier and the average power. For single carrier transmissions power ratio is not usually observed because it has a value of zero.

- Required SNR is observed to obtain the value of SNR needed by the system to reach a fixed target BER. It is useful to compare perfomances of different system where a lower required SNR means a better performance.

2.5 Other considerations

2.5.1 Noise

The noise is considered as *lumped noise* at the receiver. When we consider the lumped noise case the noise is inserted at the receiver side after WSS filter. In the lumped noise case the total amount of noise is inserted at the receiver side and WSS filters are considered as a single equivalent filter, this means that the noise is not attenuted at all. Lumped noise is considered as an upper bound with respect to *Equally distributed* noise where the total amount of noise is distributed among the WSS filters.

2.5.2 Equalization

At the receiver side the signal is not ideal but it is affected by distortions caused by the transmission over the channel. WSS filtering effects are the main sources of phase and amplitude distortions. Because of bandwidth narrowing, signal power is attenuated at the edges of the channel spectrum and so ISI phenomena are present. The result is that system performances decrease with an increase of the required SNR needed to reach the target BER. Taking these premises into consideration the equalization aims to mitigate ISI effects with a compensation of spectrum attenuation. The function of the equalizer is to estimate the channel frequency response sending a known bit sequence over the channel in order to define tap weights. This process can be iterative in order to adapt the equalizer to processed data for a better mitigation of channel effects. In this work the equalizer is always applied to improve performances.

Chapter 3

Simulations on the coherent optical system exploiting subcarrier multiplexing

Simulations have been performed using MATLAB and the OptDSP library. This library permits to simulate fiber optic communication systems giving the possibility to configure the transmitter and receiver for different scenarios.
The working method has been organized starting from a general investigation and so the focus was moved to investigate deeply how the WSSs affect performances. The presence of one or more WSSs is relevant and performances depend on filtering effects introduced. The first attempt has been to change the central frequency of the spectrum of the WSS inserting a defined frequency offset. In a second moment the same study was done with a randomic approach. For each WSS the frequency offset was randomly extracted with a normal distrubtion and variance equal to 0.5 and 1. The study was not only on the simple set-up made up of a single transmitter-receiver system. New set-ups have been implemented, for example using a theoretical optimization of subcarriers before the transmission or applying the theoretical optimization after a first flat power transmission. Theoretical method is useful to understand quickly the behaviour of the system, it has been used as starting point and for other investigations it has been used as a reference. Theoretical results are not based on the simulation of the transmission-receiver chain, but it takes account of analytical definitions of the observed measures. The system was set in order to always use the equalizer and with the lumped noise insertion. WSS is configured with an optical transfer function(OTF) babdwidth of 10.4 GHz. The bandwidth of the WSS has been changed depending on symbol rate: 32 and

64 GBaud. With 32 GBaud transmission the bandwidth was set to 37.5 GHz while with 64 GBaud transmission the bandwith was set to 75 GHz. The OTF bandwidth is always the same so that the steepness of the function does not change. The FEC Over Head and the target BER are set to 0.28 and $1.76 \cdot 10^{-2}$ respectively.

3.1 General investigation

The aim of the first part is to understand the behaviour of the system. The set-up used is very simple with a transmitter and a receiver in a back to back configuration. The performances are analyzed observing the required SNR to reach the target BER previously defined.
Four different cases of bit rate are mainly considered:

- 200G:32 Gbaud,16-QAM
- 300G:32 Gbaud,64-QAM
- 400G:64 Gbaud,16-QAM
- 600G:64 Gbaud,64-QAM

The variation of symbol rate and modulation means also the variation of the bit rate of the transmitted signal. The cases at 32 Gbaud have a bit rate of 200G and 300G where the modulation format is respectively 16-QAM and 64-QAM while for the cases at 64GBaud the bit rate is 400G and 600G depending if the modulation format is 16-QAM or 64-QAM. The goal, as written before is to test the system and, for each of the abovementioned cases, performaces for single and multi-subcarrier are tested. The upper limit for the number of subcarriers is dictated by [9] where it is shown that to have a minimum bit rate for subcarrier in the range of 2-4 GBaud. In order to have a symmtetry, subcarrier number is always even and so starting from the single carrier case the number of subcarriers increases as a power of 2 up to 16 or 32 depending on the corresponding symbol rate. Values of required SNR without WSS can be seen as reference in order to evaluate future simulations.

Transmission without WSS

In the first simulation there are no WSS and so the signal is not affected by filtering effects at the edges of the spectrum. The system has been tested with flat power and power loading strategy, results are shown in figure 3.1.
This case without filtering effects, as written above, is the starting point and it can

be seen as the best scenario and so as a reference to understand penalties caused by filtering effects introduced when there is a cascade of WSS.
As it is possible to see, changing the number of subcarriers the performance does not change because all the subcarriers have the same amount of power and none of them are penalized. All the curves are overlapped and the power loading strategy is unnecessary because it is more suitable when the subcarriers are penalized due to attenuation introduced by filtering effects. What is important at this point is to observe how the modulation and the bit rate influences the required SNR. Higher order modulation formats are more sensitive to distortion effects because symbols are closer and so in the demodulation stage there is an higher number of errors leading to an increase of the BER.
In this case we can observe that the value of required SNR depends on the modulation format. With 16-QAM the required SNR is 13 dB while in the 64-QAM case it is 19 dB as summarized in table 3.1

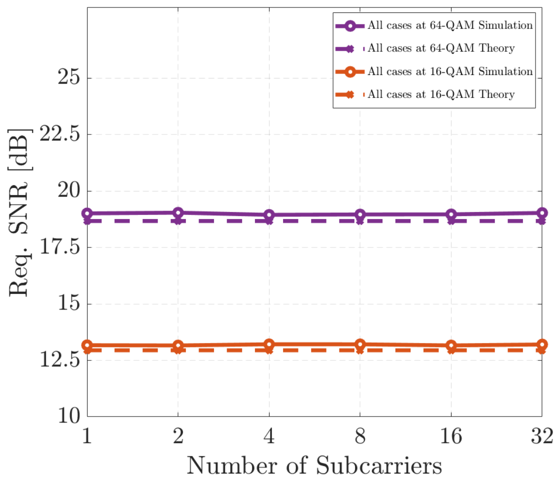


Figure 3.1: *Required SNR of all the considered cases with same power and power loading strategy without WSS.*

		Theory [dB]	Simulation [dB]
32GBaud	**16-QAM**	12.95	13.15
	64-QAM	18.65	19
64GBaud	**16-QAM**	12.95	13.15
	64-QAM	18.65	19

Table 3.1: *Values of required SNR [dB] for the cases without WSSs*

Transmission with cascaded WSSs

The next step is to simulate a transmission where the signal crosses one or more cascaded ROADMs.
In the previous section the only important factors are the symbol rate and the modulation format. The behaviour of the system is different when a cascade of WSSs is introduced and, in addition to symbol rate and modulation format also the number of subcarriers and optimization strategies are relevant.
As we can observe in figure 2.6, the external subcarriers suffer more the filtering effects due to the cascaded WSS, in particular when the number of WSS increases. This means that also the required SNR increases. To mitigate this effect we can take advantage of bit and/or power loading optimization. As a consequence the

		4 WSS	**8 WSS**	**12 WSS**
32GBaud	**16-QAM**	15.78	20.67	28.08
	64-QAM	21.78	28.98	—
64GBaud	**16-QAM**	13.49	14	14.66
	64-QAM	19.33	19.89	20.8

Table 3.2: *Required SNR[dB] for single carrier cases with the increase of the number of cascaded WSSs.*

filtering effect of the cascade of WSSs introduces a penalty in the required SNR. Required SNR increases in different ways depending on the specific case of symbol rate and modulation. First of all, observing single carrier cases we can see that the required SNR increases when the number of cascaded WSS is higher. As expected there is no difference between the flat power and power loading strategy. The bit rate is an important factor, in fact transmitting with a symbol rate of 64 Gbaud the required SNR increases less then the 32 Gbaud cases. With 8 WSSs the penalty of the cases at 200G and 300G with respect to the results in figure 3.1 is 7 dB higher, while in 400G and 600G the transmission can occur, as summarized in table 3.2.
If we observe the role of the subcarriers we can say that there is a general trend where at first the required SNR continues to increase, when the number of subcarriers is higher than 8 the performances are better. We can also appreciate the effect of the power loading strategy with more than 2 subcarriers. Power loading strategy optimizes the power allocation so that less power is allocated on more penalized subcarriers(on the edges) limiting the filtering effect. Joining togheter the use of more subcarriers with optimization strategies we can obtain good results in the limitation of filtering effects. At this point only power loading has been used because the goal is only to observe the general behavior of the system, in fact there

is also the possibility, as we will see in the next chapters, of using other optimization strategies. Bit and power loading, for example, optimizes also the modulation format for each subcarrier allocating low order constellations on the external subcarriers.
The aim of this preliminary study is to find some specific cases and to deeply investigate the WSSs effects in these cases. Considering the multi-subcarrier transmission we will consider the cases with a symbol rate per subcarrier of 2-4 GBaud corresponding to the cases with 16 or 32 subcarriers where the required SNR decreases with respect to what happens for a lower number of subcarriers. Single carrier cases will be useful in order to have a reference and to understand if there is an advantage in using the multi-subcarrier approach.

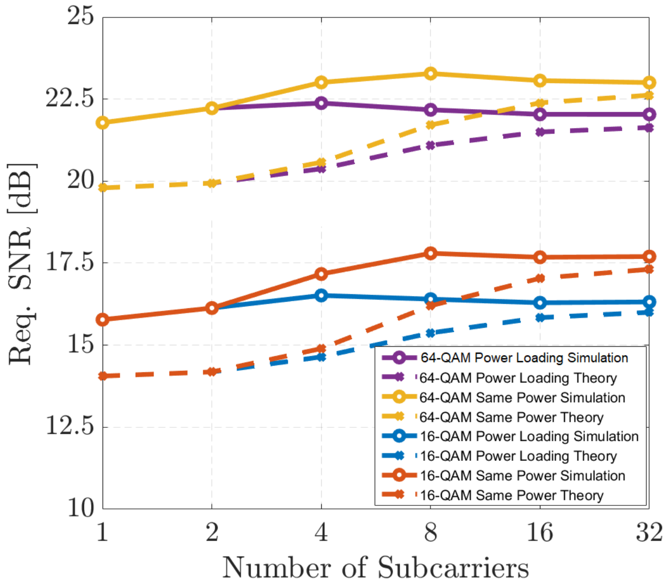


Figure 3.2: *Required SNR of simulation and theory for different cases of number of subcarriers with 4 cascaded WSSs at 32 GBaud.*

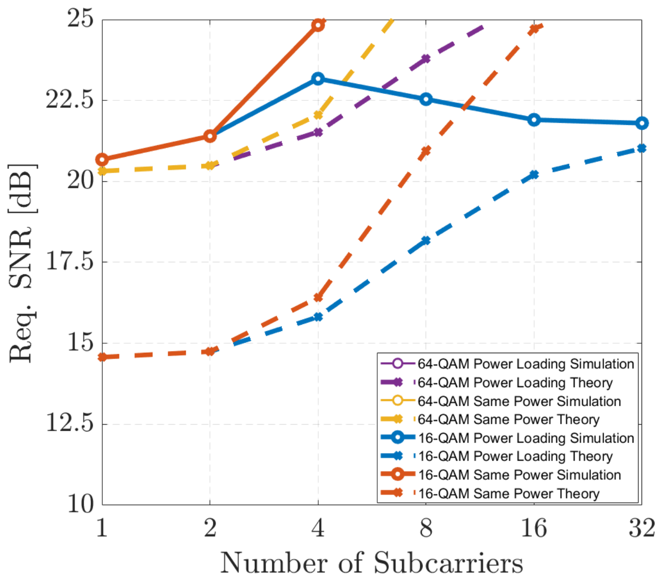


Figure 3.3: *Required SNR of simulation and theory for different cases of number of subcarriers with 8 cascaded WSSs at 32 GBaud.*

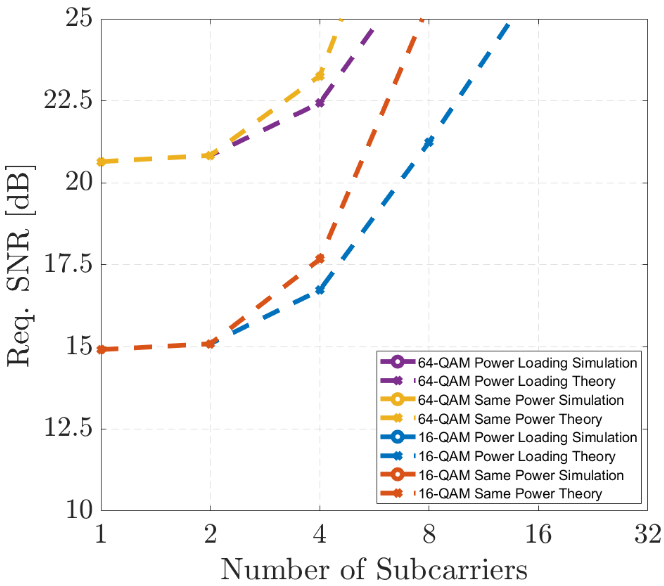


Figure 3.4: *Required SNR of simulation and theory for different cases of number of subcarriers with 12 cascaded WSSs at 32 GBaud.*

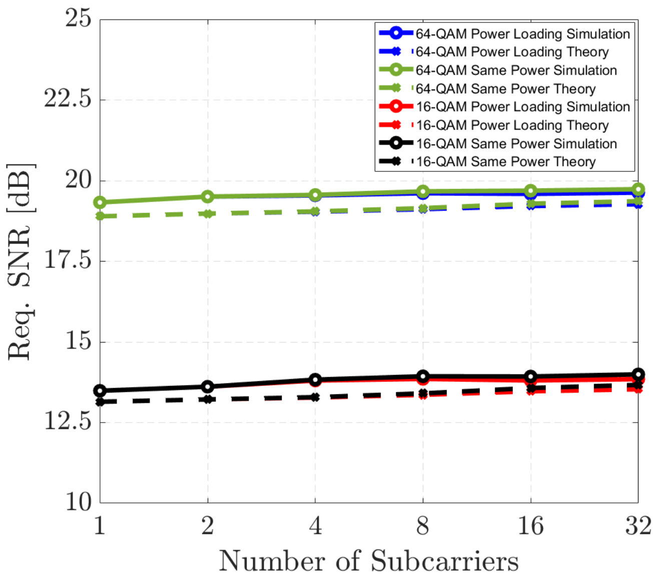


Figure 3.5: *Required SNR of simulation and theory for different cases of number of subcarriers with 4 cascaded WSSs at 64 GBaud.*

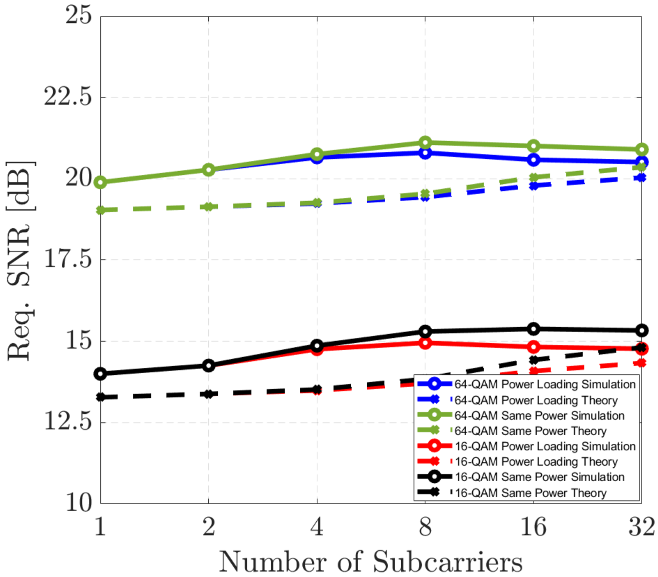


Figure 3.6: *Required SNR of simulation and theory for different cases of number of subcarriers with 8 cascaded WSSs at 64 GBaud.*

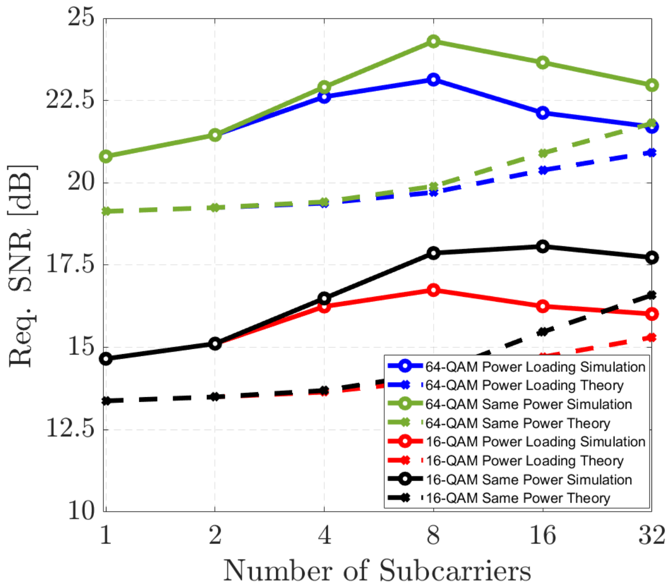
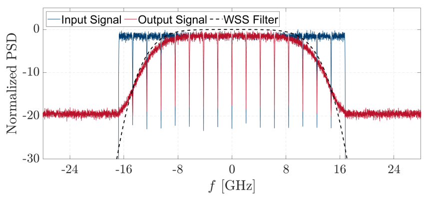


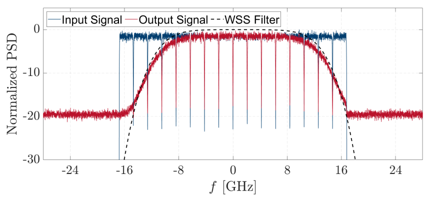
Figure 3.7: *Required SNR of simulation and theory for different cases of number of subcarriers with 12 cascaded WSSs at 64 GBaud.*

3.2 Deterministic analysis on the impact of a frequency offset

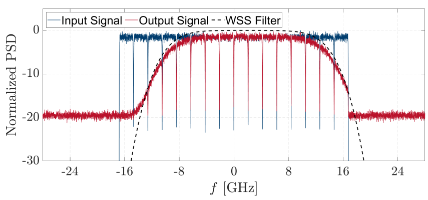
When a signal is transmitted we have to take into account different factors as the non idealities. This because transmitting on real systems there are some effects introduced not only by the characteristic of the channel but also by defects of the instrumentation. In general, in an ideal scenario, the transmitted signal and the equivalen WSS of the cascade are alligned. Unfortunately, in a realistic scenario, the filter can suffer of a frequency detuning, which has to be taken into account in our simulations. To simplify the analysis, we first assume the frequency offset to be zero (0 GHz). In a real case, because of oscillations of the laser or because of defects of the WSS it could be that some frequency offsets are present. This means that the filtering effect is not symmetrical and so external subcarriers on both sides are not equally attenuated. This could be a problem because symmetry properties can not be exploited anymore as shown in figure 3.8.



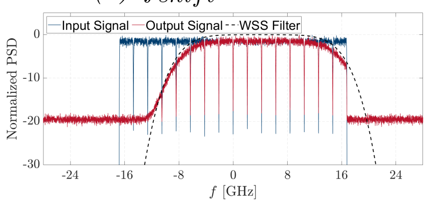
(a) f_{shift}*= 0 GHz*



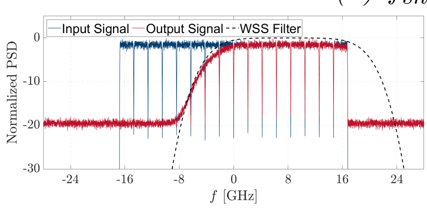
(b) f_{shift}*= 1 GHz*



(c) f_{shift}*= 2 GHz*



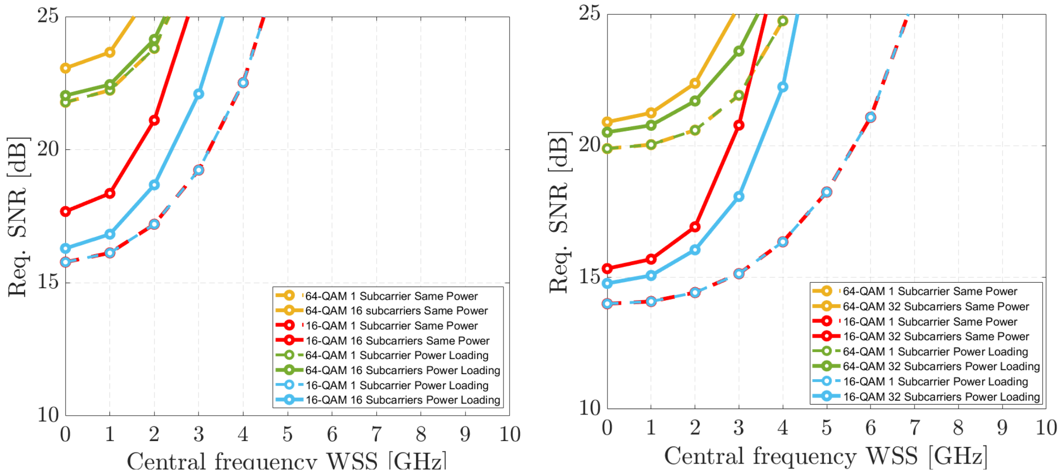
(d) f_{shift}*= 4 GHz*



(e) f_{shift}*= 8 GHz*

Figure 3.8: *Effect of different frequency offsets on a 2x16 Gbaud signal with 8 cascaded WSS.*

The spectrum of WSS shifts and so the external subcarriers are filterd differently. In the case with 8 GHz of offset,shown in figure 3.8(e), we can see that the right edge is not attenuated while on the left the first four subcarriers are completely filtered. As a consequence, to guarantee transmissions at the target BER, the required SNR increases because some subcarriers are completely or partially attenuated asymmetrically.
The system previously tested has been now tested introducing a frequncy offset. From the previous general investigation, as written, some specific cases has been chosen.



(a) Symbol rate: 32 GBaud *(b) Symbol rate: 64 GBaud*

Figure 3.9: *Effect of the frequncy offset on the required SNR with 4 cascaded WSSs in the case with a symbol rate of 32 GBaud(a) and 8 cascaded WSSs with a symbol rate of 64 GBaud(b).*

Four main cases are considered, each of them with different bit rates depending on the different combination of symbol rate and modulation format: 200G, 300G, 400G and 600G as listed in section 4.1. For each of them, observing the results obtained for different number of subcarriers and cascaded WSSs some relevant cases have been chosen to be widely studied. The single carrier case remains a good reference and for the multi-subcarrier transmission is considered the case with 2 GBaud per subcarrier that is a limit suggested by [9], as previously mentioned. Also the number of cascaded WSSs has been chosen observing the obtained results. For the two symbol rate values, we select the number of WSS in the cascade related to a case in which the penalty between the theoretical required SNR and the simulated one is around 3 dB. The number of cascaded WSSs is fixed and so for the cases

with a symbol rate of 32 GBaud a cascade with 4 WSSs has been chosen, while in the 64 GBaud case the cascade with 8 WSSs has been chosen.
The aim of this section is to understand the variations of the required SNR for different cases of frequency offset. In general, in real systems it is not possible to predict the presence of a frequency offset, but for the purposes of this study we assume to know it.
We consider a frequency offset varying from 0 GHz to 10 GHz with a step of 1 GHz. In figure 3.9 it is shown how the increase of the frequency offset leads to an increase of the attenuation on some subcarriers to the point that some subcarriers are completely filtered.
Since the resulting BER is calculated by averaging the BER of the subcarriers it is expected a decrease of the performance when the frequency offset is higher, as the edge subcarriers, on the left or the right respectively for a positive or negative offset, are strongly attenuated. The increase of the required SNR is nonlinear with the increase of the frequency offset as it increases exponentially. Up to 3 GHz, the frequency offset can be sustainable even if in some cases the penalty is more than 5 dB. Just to have a better idea, table 3.3 shows the amount of penalty of the required SNR with respect to the case without frequency offset.

		Required SNR [dB]				
Frequency Offset [dB]		$f_{offset} = 0$	$f_{offset} = 1$	$f_{offset} = 2$	$f_{offset} = 3$	$f_{offset} = 4$
32 GBaud	**16-QAM**	16.29	16.83(0.54)	18.68(2.39)	22.1(5.81)	-
	64-QAM	22.04	22.45(0.41)	24.14(2.1)	-	-
64 GBaud	**16-QAM**	14.77	15.07(0.3)	16.05(1.28)	18.07(3.3)	22.23(7.46)
	64-QAM	20.51	20.78(0.27)	21.7(1.19)	23.59(3.08)	-

Table 3.3: *Variation of the required SNR(dB) for different cases of frquency offset for multi-subcarrier transmission with 2 GBaud symbol rate per subcarrier applying power loading strategy. In brackets the penalty in dB repsect the required SNR without frequency offset*

In table 3.3 there are some missing values because they are out of the SNR window simulated and so those values are not reliable because they are the result of an extrapolation.
In real scenarios, these frequency offsets, caused by oscillations of the laser or of the ROADM, do not assume such large values but in general they are limited to 1 or 2 GHz. What we see from the table is that for small values up to 1 GHz the increase of the required SNR is small and this means that the system is robust enough.

3.3 Statistical analysis on the impact of a frequency offset

So far we have seen that a cascade of WSSs introduces penalties because of the filtering effects. These effects are more relevant with the increase on the number of cascaded WSSs. Losses increase when the equivalent filter is not alligned with the transmitted signal,that is to say that it is affected by a frequency offset. We have done a first study about considering deterministic values of frequency offset but, in reality it si not possible to define them for sure.
In order to move in a more realistic case it is necessary to make further considerations. First of all we have to consider the formula 3.1 shown below, but with some modifications, representing the transfer function of the spectrum of a cascade of WSS:

$$S(f) = \left[\frac{\sigma\sqrt{2\pi}}{2}\left[\text{erf}\left(\frac{\frac{B}{2} - f + f_0}{\sqrt{2}\sigma}\right) - \text{erf}\left(\frac{-\frac{B}{2} - f + f_0}{\sqrt{2}\sigma}\right)\right]\right]^{N_{WSS}} \tag{3.1}$$

The exponent N_{WSS} is the number of cascaded WSS so that if it is 0 S(f) has a value of 1 everywhere while if it increases the spectrum became narrower. From this formula we understand that in a cascade only a WSS is modelled and then, according to the exponent we obtain the final spectrum. From a mathematical point of view this is correct but in a network each WSS is independent. The f in the formula represents the frequency slot where the WSS is placed and f_0 is the frequency offset. If we want to take into account a real case introducing a frequency offset, what happen using this formula is that modifying f_0 we assign the same frequency offset to all the WSS of the cascade. It is easy to understand that in a large network each WSS can be subject to different conditions and wear and is impossible that all of them have the same frequency offset. This problem has been solved by modifying the formula so that the equivalent spectrum of a cascade of WSSs is the result of the product of N_{WSS} different WSSs as shown in formulas 3.2 and 3.3:

$$S_{eq}(f) = \prod_{i=1}^{N_{WSS}} S_i(f) \tag{3.2}$$

$$\text{where } S_i(f) = \left[\frac{\sigma\sqrt{2\pi}}{2}\left[\text{erf}\left(\frac{\frac{B}{2} - f + f_{0,i}}{\sqrt{2}\sigma}\right) - \text{erf}\left(\frac{-\frac{B}{2} - f + f_{0,i}}{\sqrt{2}\sigma}\right)\right]\right] \tag{3.3}$$

and $f_{0,i}$ is the frequency offset affecting the i^{th} WSS of the cascade. Approaching in this way it is possible to assign different values of frequency offset to each WSS. This premise is important because tha aim is to analyze the system from a statistical point of view. This can be done if the value of the frequency offset is not a deterministic value but a random one. Values of frequency offset, as written above are not known a priori and so to create a more realistic scenario they are randomly extracted using the *randn* function of MATLAB. This function extracts normally distributed random numbers with mean 0, variance and standard deviation equal to 1. If we want to obtain values with other values of variance we can simply multiply the extracted value by the value of variance.
The statistical approach consists in testing the transmission of a signal several times measuring performances.
Two values of symbol rate are considered: 32 GBaud and 64 GBaud. Recalling simulations in previous sections two cases of cascaded WSSs are considered: 4 and 8 for 32 or 64 GBaud, respectively. To allow repeatibility, the set of frequency offset has been extracted only once and then saved to be used in all the simulations, so that this permits us to compare different cases of bit rate, optimization strategies or number of subcarriers against the variation of the frequency offset. More precisely 500 set of 8 frequency offset are exctracted obtaining a $500X8$ matrix using the first 4 values or all the 8 values depending on the number of cascaded WSSs. Two sets have been extracted, the first with a variance of 0.5 while the second one with a unitary variance. Each time the communication system is tested, the signal is transmitted 500 times and the results are so evaluated to analyze the relationship between the measured results and the frequency offset.
Different optimization strategies are available and at this point the choice was to use the bit and power loading. This strategy is very powerful because optimizes the power ratios but also, depending on the attenuation of each subcarrier, the modulation format. Bit and Power Loading strategy uses FDHMF configuration so that, maintaining the initial bit rate, on the external subcarrier there are lower order configurations.

3.3.1 Analytical Bit and Power Loading based design results

The first type of performed simulation is based on an analytical framework applying Bit and Power Loading(BPL) optimization where approximated WSS filters are used. As demonstrated in [11],the analytical framework can be used for a quick offline evaluation of losses due to filtering effects. At the same time, it provide optimization strategies which can be used to mitigate filtering effects under specific

conditions(2-4 GBaud per subcarrier). This approach is not optimal because some idealities are introduced, resulting in an upper bound scenario. Results are optimistics and can be used as a reference respct actual time-domain simulations where all the distorsion factors are considered. This first case will be callled *Theory* for simplicity. The main parameters are set as in the previous preliminary study and same cases are considered in order to test four different values of bit rate: 200G, 300G, 400G and 600G. All of them are tested for a frequency offset variance of 0.5 and 1.
The signal passes through the cascade of WSSs and so the algorithm of the bit and power loading strategy calculates power ratios and decides the modulation format of each subcarrier implementing a FDHMF configuration. The principle is to start with a fixed value of symbol rate and modulation for each of the 16 subcarriers in order to transmit a certain value of symbol rate:

- 200G:
  - 32 GBaud
  - PM-16QAM
- 300G:
  - 32 GBaud
  - PM-64QAM
- 400G:
  - 64 GBaud
  - PM-16QAM
- 600G:
  - 64 GBaud
  - PM-64QAM

After the WSS filtering and calculation of power ratios, depending on the BER experienced by each subcarrier,modulation formats are optimized so that on more penalized subcarriers(on the edges) are assigned lower order modulation formats. Bit Loading algorithm, starting from the initial modulation format(e.g. 16-QAM in 200G case) and considering power ratios, optimizes the modulation format of each subcarrier. The FDHMF configuration resulting from the optimization is chosen from some available combinations of FDHMF pre-calculated by the same algorithm. Considering all the provided sets of frequency offset, the result of the bit laoding optimization is not always the same. In fact, depending on the values of frequency offsets and power loading optimization, the best FDHMF is chosen between available ones.
In tables 3.4 - 3.7 results of the bit and power loading of each of the four cases are summarized. For simplicity only simmetrical combinations of FDHMF are considered. In these tables, for each case of variance, are shown the chosen combination of modulation formats among the available, after all the 500 sets of frequency offset have been tested.

	Modulation formats per SC															
$\sigma^2 = 0.5$ $\sigma^2 = 1$	4	8	16	16	16	32	32	32	32	32	32	16	16	16	8	4
	4	16	16	16	16	16	32	32	32	32	16	16	16	16	16	4
	4	4	16	16	32	32	32	32	32	32	32	32	16	16	4	4

Table 3.4: *Modulation formats per subcarrier for 200G signal with 16x2 GBaud.*

	Modulation formats per SC															
$\sigma^2 = 0.5$	16	32	64	64	64	128	128	128	128	128	64	64	64	64	32	16
$\sigma^2 = 1$	4	32	64	128	128	128	128	128	128	128	128	128	128	64	32	4
	8	32	64	64	128	128	128	128	128	128	128	128	64	64	32	8
	16	32	64	64	64	128	128	128	128	128	128	64	64	64	32	16

Table 3.5: *Modulation formats per subcarrier for 300G signal with 16x2 GBaud.*

	Modulation formats per SC															
$\sigma^2 = 0.5$ $\sigma^2 = 1$	4	16	16	16	16	16	32	32	32	32	16	16	16	16	16	4
	8	16	16	16	16	16	16	32	32	16	16	16	16	16	16	8
	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16

Table 3.6: *Modulation formats per subcarrier for 400G signal with 16x4 GBaud.*

	Modulation formats per SC															
$\sigma^2 = 0.5$ $\sigma^2 = 1$	32	64	64	64	64	64	64	128	128	64	64	64	64	64	64	32

Table 3.7: *Modulation formats per subcarrier for 600G signal with 16x4 GBaud.*

Depending on the values of frequency offset the spectrum of the cascade has a different central frequency and bandwidth. These changes cause a different filtering effect and so different power ratios on the 16 subcarriers.
In the single carrier transmission there is no need to apply bit and power loading while it is powerful in the multi-subcarrier(MSC). From tables 3.4 - 3.7 is possible to see the effects of bit loading because of filtering effects. The analysis is carried out considering only 16 subcarriers, also for the 64 GBaud cases because the 32 subcarriers transmission is high computationally demanding. That said, the limit of 2-4 Gbaud per subcarrier is respected. At a first view of tables 3.4 - 3.7 we can see the effect of higher bit rates where there are higher order modulation formats

also in the subcarriers on the edges.
For each of the 500 analized cases we obtain a triplet composed of -3 dB bandwidth, central frequency of the WSS spectrum and the required SNR to reach a BER of $1.76 \cdot 10^{-2}$.
Figures 3.10 - 3.12 show the results of 200G case in single carrier and MSC scenarios with both values of frequency offset variance. First of all we can distinguish the difference of performances when the the variance increases. A higher value of variance means that values of frequencies offset for each WSS are higher with a decrease of performances. As expected, when the central frequency starts to increase, i.e. the separation between its value and the nominal one (0 GHz) grows,the required SNR increases as well. The same relationship is present between the required SNR and the -3 dB bandwith of the equivalent spectrum of the cascade of WSSs. In the latter case there is an inverse proportion in fact, when the bandwidth is narrower the required SNR increase because of the greatest filtering effects on the edges. The lowest value of required SNR corresponds to a case where the equivalent spectrum of the filter is very similar to the spectrum without frequency offset. Observing results of MSC transmission at 200G the lowest value of required SNR is 15.1 dB with a -3 dB bandwidth of 25.2 GHz and the central frequency about 14 MHz. In the worst case, the required SNR is 16.4 dB, the central frequency is -2.1 GHz and B_{-3dB} is 20.1 GHz. From there we can see that there is a linear relationship between the B_{-3dB} and the required SNR while there is a parabolic relationship between the f_c and the required SNR.
In this case, the required SNR is lower when single carrier is used instead of the MSC, with a required SNR of 14.1 dB in ideal conditions. The MSC transmission introduces a penalty of about 1 dB respect the single carrier one.
In the case of the 300G signal, general considerations about the triplet composed of required SNR, f_c and B_{-3dB} are quite similar. To deliver this higher bit rate, a modulation format with higher cardinality is needed, therefore also the BER increases. In the single carrier transmission the better value required SNR is 19.8 dB that is practically the same value of the case without frequency offset. The value of B_{-3dB} is 25.25 GHz with a central frequency of -27 MHz that are values very close to that of the lowest value of required SNR of 200G.
The lowest value of required SNR in the MSC case is 20.85 dB, in fact observing the banwidth and the central frequency we have 25.26 GHz and -27 MHz respectively, values close to the other best cases. Also in this case the use of MSC configuration introduces a penalty of about 1 dB with respect to the single carrier signal.
These first two configurations with 2 GBaud per subcarrier have a lot of similarities if we observe the trend of the required SNR with respect to the introduction of a

frequency offset in the WSSs. Due to a different bit rate and the use of different modulation format order, the required SNR of 300G transmission is shifted to higher values.
The other two cases have a bit rate of 400G and 600G with a symbol rate of 64 GBaud. The signal passes through a cascade of 8 WSSs with a bandwidth of 75 GHz. In the MSC transmission the number of subcarriers is 16 with 4 GBaud per subcarrier.
The general trend in the cases shown in figures 3.16 - 3.19 is similar to the one shown previously. In the 400G transmission the lowest values of required SNR are 13.3 dB in single carrier and 13.8 dB in MSC transmission. These values correspond to a frequency offset of 63 MHz for single carrier and 168 MHz for MSC with a B_{-3dB} of 59.76 GHz. The penalty of the required SNR of the worst case with respect to the best values is in the range of 0.1-0.3 dB depending on the considered variance. In these cases, as in the two previous cases, the -3 dB bandwidth is narrower and f_c is in a range between 170 MHz and 1.67 GHz.
In the 400G bit rate transmission observing figure 3.16 it is possible to see a "jump" in the values of required SNR in the range of B_{-3dB} between 59.6 GHz and 59.8 GHz; this jump may be due to a different impact of the discretized WSS filter, the approximation assumed in the theoretical framework. In the last case, whose results are shown in figures 3.19 - 3.21, the required SNR fluctuates between 19 dB and 19.1 dB in case of single carrier, while in MSC case the required SNR ranges between 19.4 dB and 19.9 dB. Lowest values of required SNR correspond to a B_{-3dB} about 59.76 GHz while the central frequency of the equivalent spectrum oscillates between 38 MHz and 170 MHz. All the cases with a symbol rate of 64 Gbaud have a penalty of the MSC transmission with respect to single carrier one of 0.4-0.5 dB. In the next sections, considering different set-ups, these configurations will be tested with a simulation where power ratios are optimized such that SNRs are minimized. The aim is to evaluate performances in the same way seen in this section analyzing the relationship between B_{-3dB}, f_c and required SNR for each set of frequency offset tested.

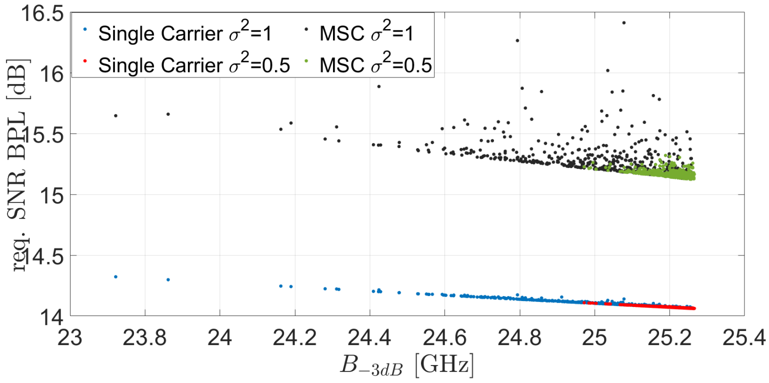


Figure 3.10: *Required SNR versus -3 dB bandwidth for a 200G transmission, comparing single carrier and MSC strategiesfor both values of variance considered.*

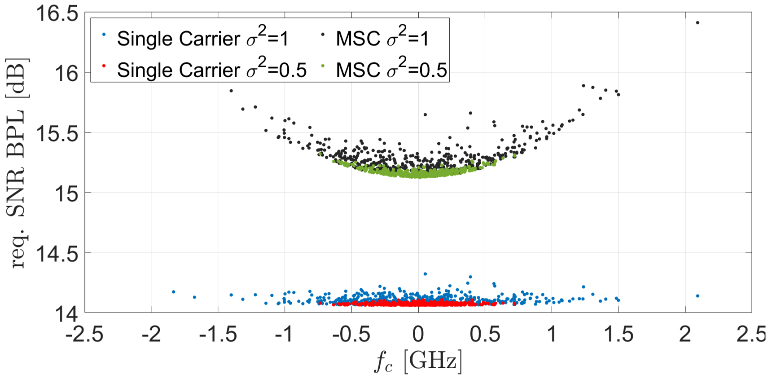


Figure 3.11: *Required SNR versus central frequency for a 200G transmission, comparing single carrier and MSC strategies for both values of variance considered.*

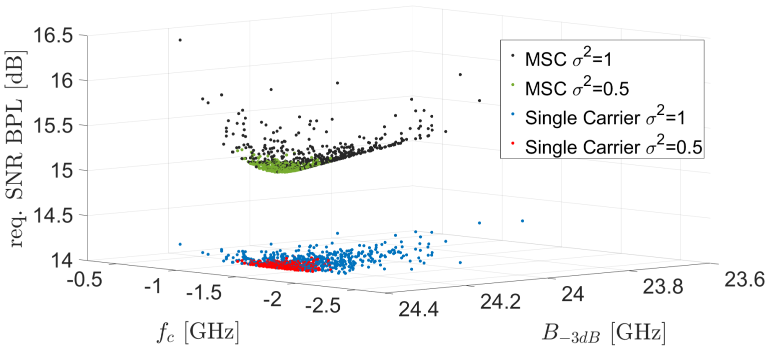


Figure 3.12: *Required SNR versus central frequency versus -3 dB bandwidth for a 200G transmission, comparing single carrier and MSC strategies for both values of variance considered.*

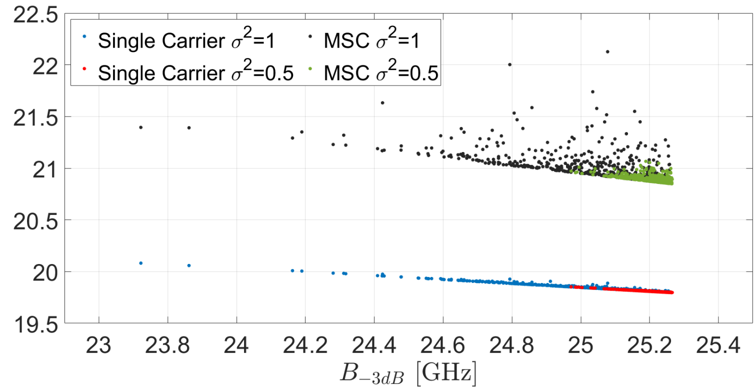


Figure 3.13: *Required SNR versus -3 dB bandwidth for a 300G transmission, comparing single carrier and MSC strategiesfor both values of variance considered.*

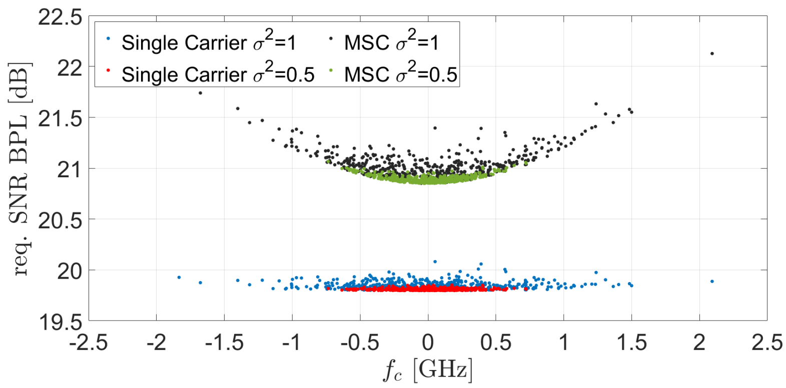


Figure 3.14: *Required SNR versus central frequency for a 300G transmission, comparing single carrier and MSC strategies for both values of variance considered.*

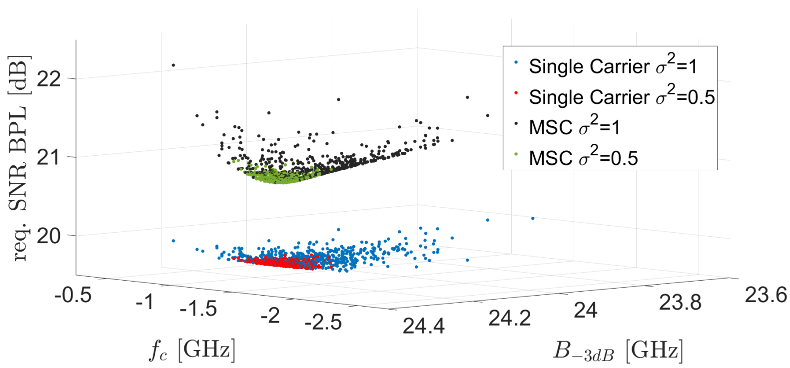


Figure 3.15: *Required SNR versus central frequency versus -3 dB bandwidth for a 300G transmission, comparing single carrier and MSC strategies for both values of variance considered.*

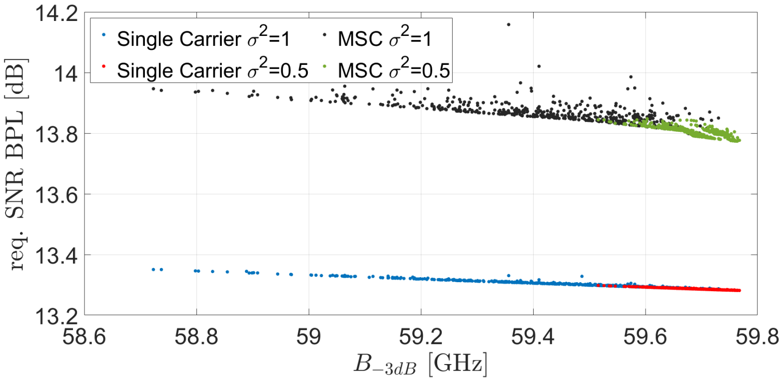


Figure 3.16: *Required SNR versus -3 dB bandwidth for a 400G transmission, comparing single carrier and MSC strategiesfor both values of variance considered.*

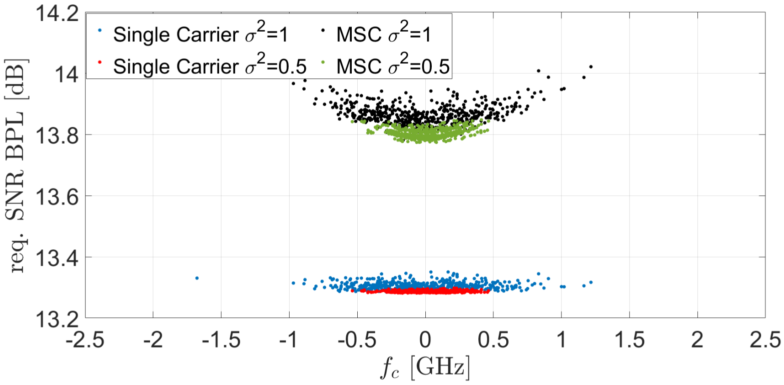


Figure 3.17: *Required SNR versus central frequency for a 400G transmission, comparing single carrier and MSC strategies for both values of variance considered.*

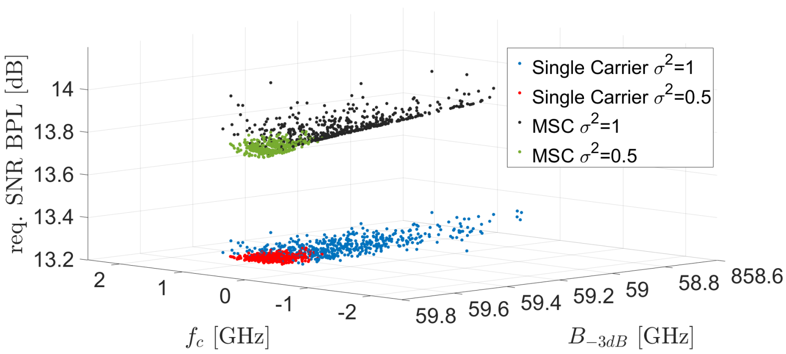


Figure 3.18: *Required SNR versus central frequency versus -3 dB bandwidth for a 400G transmission, comparing single carrier and MSC strategies for both values of variance considered.*

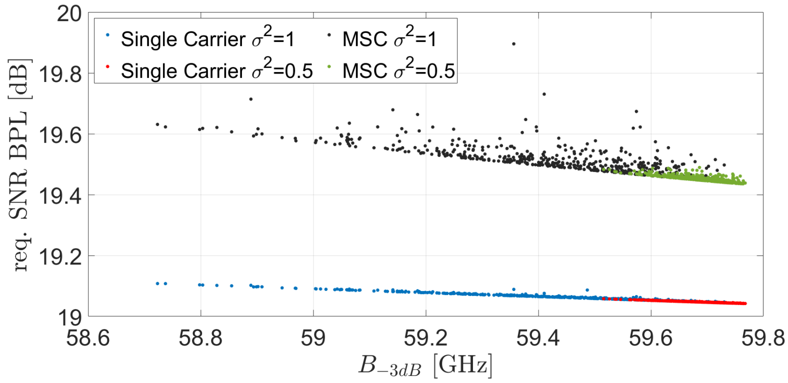


Figure 3.19: *Required SNR versus -3 dB bandwidth for a 600G transmission, comparing single carrier and MSC strategiesfor both values of variance considered.*

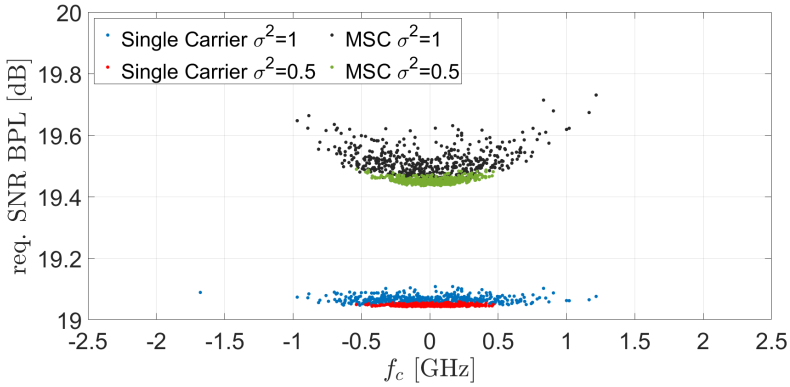


Figure 3.20: *Required SNR versus central frequency for a 600G transmission, comparing single carrier and MSC strategies for both values of variance considered.*

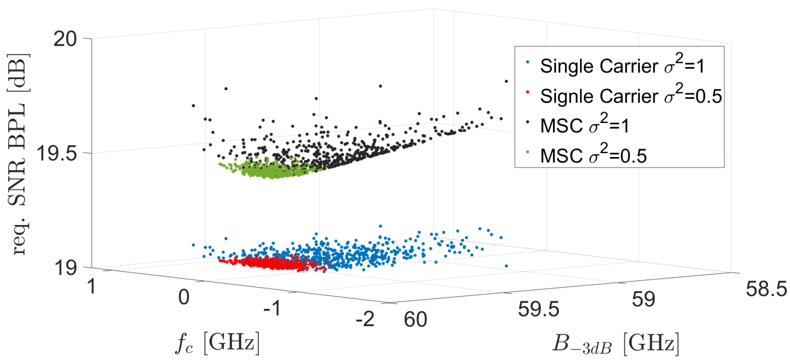


Figure 3.21: *Required SNR versus central frequency versus -3 dB bandwidth for a 600G transmission, comparing single carrier and MSC strategies for both values of variance considered..*

3.3.2 Time-domain simulation with analytical BPL optimization

After the first study based on analytucal results the work goes on testing new set-ups. The next one is composed basically by two stages: an analytical one as before and then a proper time-domain simulation. This set-up will be called *Simulation* for simplicity.
In the first stage the signal is modelled with a BPL strategy providing all the information as the number of subcarriers, the symbol rate and the bit rate. Other parameters as the noise insertion and the equalizer are always the same and so the system is configured with lumped noise and the equalizer is used. Thanks to bit and power loading optimization applied with a theoretical approach we obtain power ratios and modulation formats to provide as input to the simulation stage. As seen before power ratios are obtained and then based on their values, FDHMF is exploited for the MSC signal. The analytical optimization is performed without frequency offset because at this stage provide us an off line optimization. This means that the theoretical modelling is performed once.
Then in the second stage, the values obtained from the design are used for a time-domain simulation, where all the transmission effects are taken into account.
The approach is statistical as for theory in the previous section applying random frequency offset set. The set of frequency offset is the same used above in order to understand the behaviour of this new system considering the same impact of filtering effects in cascaded WSSs. When we transmit in single carrier there is no need to apply the signal modelling because bit and power loading is not applied, so that the signal is like a flat power penalized by the filtering effect of the cascade of WSSs. In table 3.8 the optimized power ratios and the result of the bit loading for the four cases of bit rate are shown.

200G	**PRs**	-0.5044	1.3300	-0.1636	-0.9154	-1.2073	-1.2976	0.9350	0.9311
	M	4	16	16	16	16	16	32	32
300G	**PRs**	0.3588	-0.3350	-0.1726	-0.9041	-1.1894	0.6266	0.6072	0.6046
	M	16	32	64	64	64	128	128	128
400G	**PRs**	2.0651	0.0535	-0.4458	-0.4796	-0.4807	-0.4807	-0.4806	-0.4807
	M	16	16	16	16	16	16	16	16
600G	**PRs**	0.4217	0.0439	-0.3820	-0.4114	-0.4119	-0.4121	-0.4121	1.2514
	M	32	64	64	64	64	64	64	128

Table 3.8: *Optimized modulation formats and power ratios [dB] per subcarrier. Only the results for the first 8 subcarriers are shown since the configuration is symmetrical.*

Before the optimization of 200G and 400G signals all the subcarriers are set with a 16-QAM modulation format with 32 GBaud and 64 GBaud respectively. In the other two cases the optimization starts using 64-QAM modulation format for all the subcarriers. Results are shown following the same strategies seen previously. Considerations will be made observing the required SNR and its relationship with the variations of f_c and B_{-3dB} due to frequency offset. From figures 3.22 - 3.33 it is possible to see how the behaviour of the system follows the trend seen for the analytical results. Obviously what is expected is a penalty with respect to the theory. The first consideration about these results is that there is a difference of performances when the bit-rate increases. In case of 200G and 300G net rates, it is convenient to exploit MSC instead of single carriers, whereas this is no longer true for 400G and 600G systems. In fact, required SNR of single carrier transmission is lower because in these cases the symbol rate is higher and then the single carrier configuration is strong. To gain an advantage from MSC we need a number of subcarriers higher than 32. Moving into specific details in 200G multi-subcarrier transmission, lower bound of required SNR is 15.6 dB, while in case of single carrier the required SNR is about 15.8 dB. Varying the central frequency and the -3 dB bandwidth, there is not a significative variation of the required SNR.
In 300G transmission the lowest values of required SNR for single and multi-subcarrier mode are respectively 21.8 dB and 21.4 dB but in this case we observe that in single carrier transmission the required SNR increases more than in the multi-subcarrier case for a narrower -3 dB Bandwidth. The required SNR penalty is between 0.4 dB and 0.5 dB in the region for most of the cases with a -3 dB bandwidth varying between 25.25 GHz and 25 GHz. In 400G transmission the required SNR related to a B_{-3dB} of 59.75 GHz, which is the lowest value, is 15 dB in MSC scenario, while in single carrier scenario the lowest value is 14 dB. The penalty introduced by MSC is sligthy less than 1 dB. In a 600G transmission, as shown in figure 3.31,the penalty of the multi-subcarrier transmission with respect to the single carrier one is about 0.7 dB. With a single carrier transmission the minimum required SNR is 19.9 dB while with 16 subcarriers it is 20.6 dB, in both cases with an equivalent B_{-3dB} of 59.76 GHz and a central frequency close to 100 MHz. We can compare multi-subcarrier performances of this set-up with the analytical one seen in the previous section just to have an idea of the penalty introduced. As expected, analytical results has always better performances, in fact at this point 200G simulation has a penalty of 1.3 dB, 300 G is penalised by 0.51 dB while 400G and 600G have a penalty of 1.2 dB and 1.1 dB respectiely. Values of required SNR with the respective B_{-3dB} and f_c draw a paralaboloid and from the comparison we can observe that from results of these first two set ups we have two similar paraboiloids shifted because of the required SNR penalty.

Once the time-domain simulation with anaytical modelling has been tested, we can observe what happen if we test the analytical framework with an analytical pre-optimization without frequency offset as done above. While thoretical results of section 3.3.1 are obtained applying bit and power loading for each of the 500 frequency offset cases, in this case the optimization is done once. Power and bit allocation is then the starting point for the transmission, therefore we expect better results (lower required SNR). Results are shown in the next section and the set-up will be called *Optimized Analytical*.

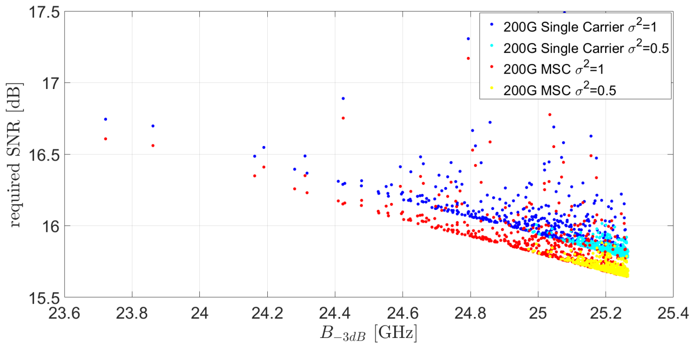


Figure 3.22: *Required SNR versus -3 dB bandwidth for a 200G time-domain simulation, comparing single carrier and MSC strategiesfor both values of variance considered.*

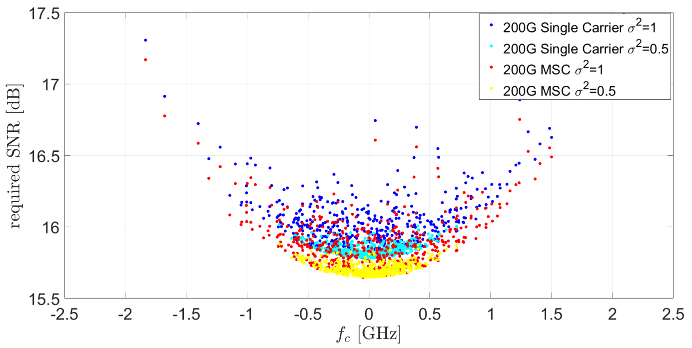


Figure 3.23: *Required SNR versus central frequency for a 200G time-domain simulation, comparing single carrier and MSC strategies for both values of variance considered.*

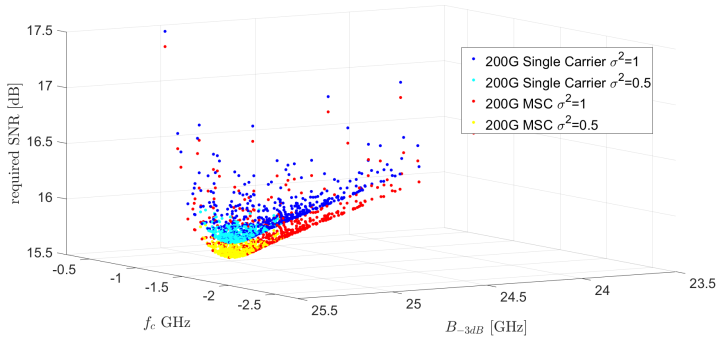


Figure 3.24: *Required SNR versus central frequency versus -3 dB bandwidth for a 200G time-domain simulation, comparing single carrier and MSC strategies for both values of variance considered.*

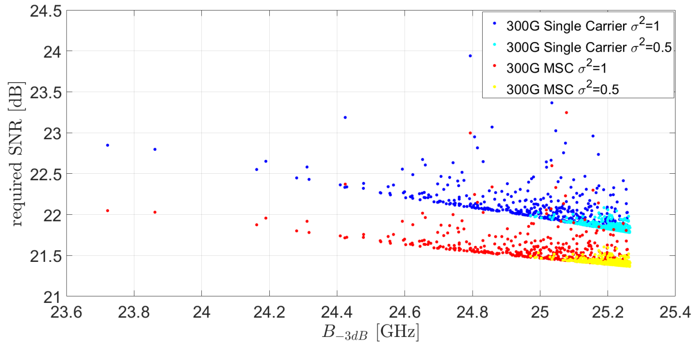


Figure 3.25: *Required SNR versus -3 dB bandwidth for a 300G time-domain simulation, comparing single carrier and MSC strategiesfor both values of variance considered.*

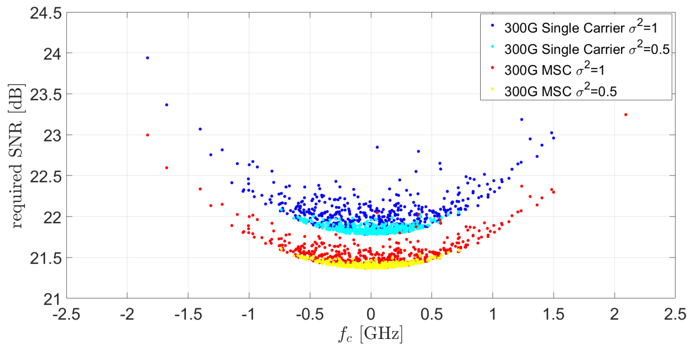


Figure 3.26: *Required SNR versus central frequency for a 300G time-domain simulation, comparing single carrier and MSC strategies for both values of variance considered.*

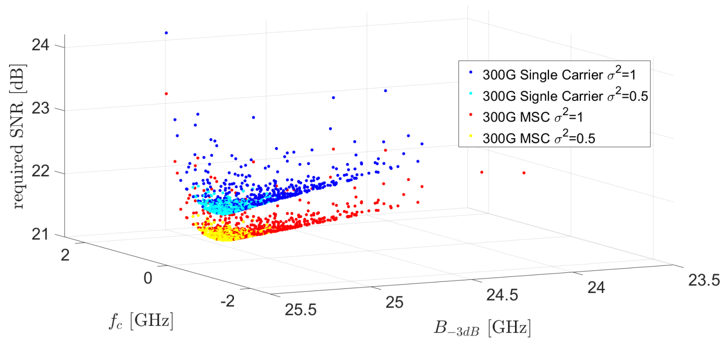


Figure 3.27: *Required SNR versus central frequency versus -3 dB bandwidth for a 300G time-domain simulation, comparing single carrier and MSC strategies for both values of variance considered.*

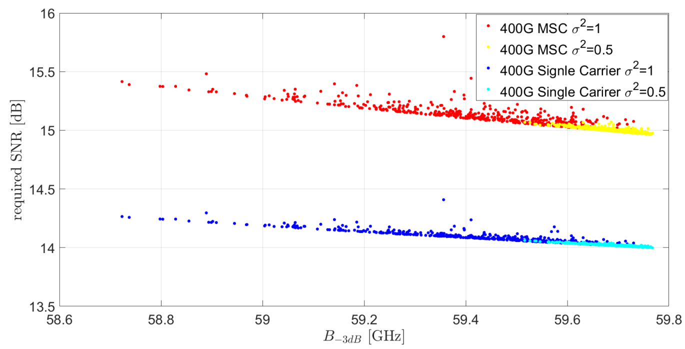


Figure 3.28: *Required SNR versus -3 dB bandwidth for a 400G time-domain simulation, comparing single carrier and MSC strategiesfor both values of variance considered.*

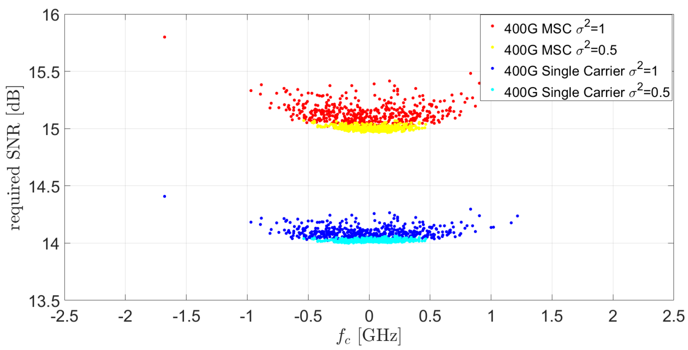


Figure 3.29: *Required SNR versus central frequency for a 400G time-domain simulation, comparing single carrier and MSC strategies for both values of variance considered.*

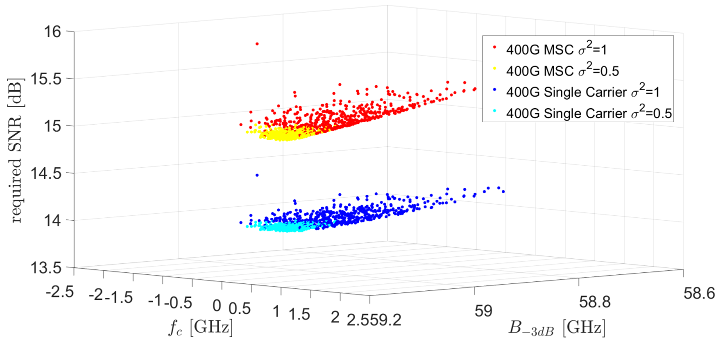


Figure 3.30: *Required SNR versus central frequency versus -3 dB bandwidth for a 400G time-domain simulation, comparing single carrier and MSC strategies for both values of variance considered.*

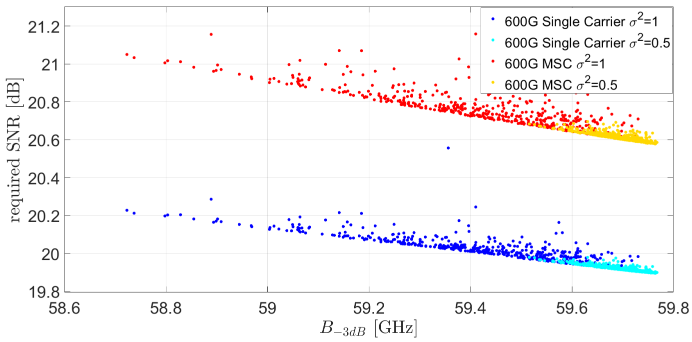


Figure 3.31: *Required SNR versus -3 dB bandwidth for a 600G time-domain simulation, comparing single carrier and MSC strategiesfor both values of variance considered.*

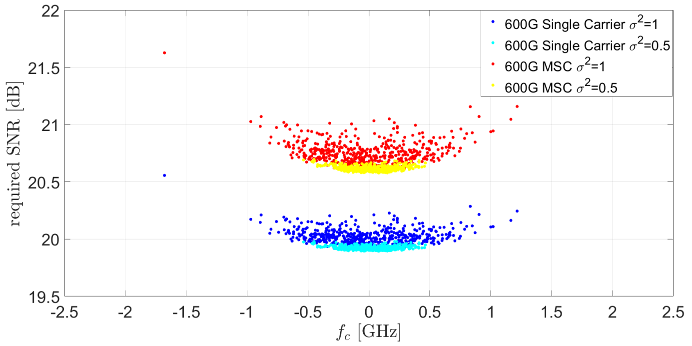


Figure 3.32: *Required SNR versus central frequency for a 600G time-domain simulation, comparing single carrier and MSC strategies for both values of variance considered.*

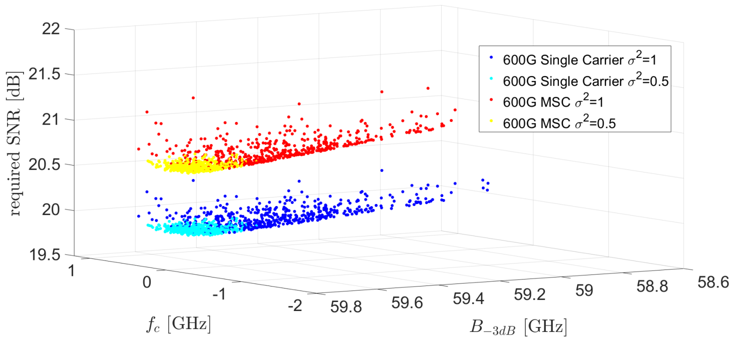


Figure 3.33: *Required SNR versus central frequency versus -3 dB bandwidth for a 600G time-domain simulation, comparing single carrier and MSC strategies for both values of variance considered.*

3.3.3 Time-domain simulation with analytical BPL feedback-based design

As in a realistic system, the transmission of the MSC signal takes place considering each subcarrier with the same power and modulation format configuration. The result of this first time-domain simulation is represented by mean power of each subcarrier at the receiver. Each mean power level assumes a value related to the filtering effect on each subcarrier. This transmission is useful to test the channel These powers are exploited by the theoretical framework for the BPL analytical design to optimize the power ratios and the mdulation formats. At this point, the values of power ratios and the optimized modulation formats, are provided for the re-transmission. This system is composed of three stages, where the second stage acts as an analytical BPL feedback. All the three stages are tested taking into consideration the presence of the frequency offset. This set-up will be called *Analytical feedback based simulation*. In this section we focus on multi-subcarrier transmission, which results for all the tested set-ups are shown in figures 3.35 - 3.42. We can do a first analysis comparing results of this last set-up with the previous ones. First of all we can observe that performances of the *Optimized Analytical* set-up are almost overlapped to theory. Let us observe the comparison of results of the considered set-up for the 4 different bit rate values.
In figures 3.35 and 3.36 , observing the cases at 200G, it is shown that for lowest values of B_{-3dB} around 25.26 GHz, required SNR of *Analytical feedback-based simulation* set-up and *Analytical optimized simulation* converge to the same lowest value of 15.65 dB with a central frequency around 50 MHz. As the B_{-3dB} decreases, required SNR of *Analytical feedback-based simulation* set-up increases with a less

steep trend than the *Analytical optimized simulation* one. In the transmission with 300G, performances of *Analytical optimized simulation* and *Analytical feedback-based simulation* are very similar and the surfaces defined by required SNR, B_{-3dB} and f_c are almost overlapping. In both these two first cases the penalty introduced by the *Analytical feedback-based simulation* with resepct to the *Theory* is about 0.5 dB of required SNR. Moving to signals with a symbol rate of 64 GBaud (4 GBaud per Subcarrier) the *Analytical feedback-based simulation* system has better performances with respect to the *Analytical optimized simulation*. In 400G transmission the penalty passes from 1.6 dB of *Analytical optimized simulation* to 0.8 dB of the *Analytical feedback-based simulation* adding that in this case the increase of the required SNR compared to the decrease of the equivalent B_{-3dB} is very close to the *Theory*. In 600G transmission the first consideration is about a bug in the *Analytical feedback-based simulation* set-up where in the range of B_{-3dB} between 59.7 GHz and 59.5 GHz, required SNR is too high. The problem could be traced back to discretized filters used by the analytical feedback. Not considering this problem, in other regions of B_{-3dB} the penalty respect *Theory* is about 0.8 dB.

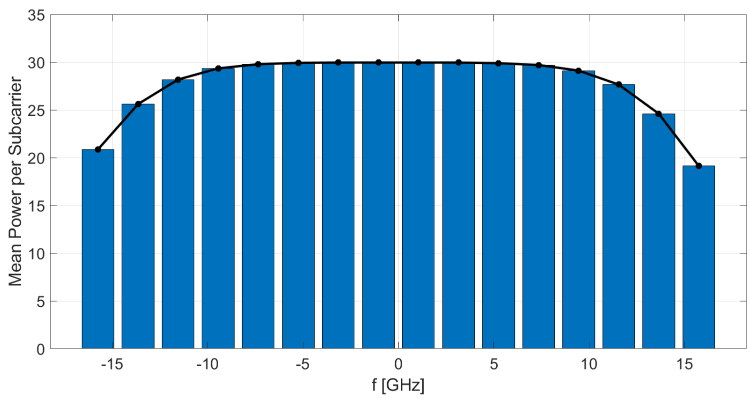


Figure 3.34: *Interpolation of power levels per subcarrier.*

Surfaces defined by B_{-3dB}, f_c and required SNR have a parabolic shape. This characteristic is present in all the cases analyzed up to now. In figure 3.43 for each bit rate case is shown how the surfaces resuting from MSC transmission,can be more or less overlapping. We can make a qualitative observation, in fact in the region where f_c is between -0.5 GHz and 0.5 GHz surfaces are well overlapping when shifted. Before to continuing with the analysis it is useful to take a closer look at the values of the B_{-3dB} and f_c calculated and used up to now for shown results. Up to now,the values of B_{-3dB} and f_c have been calulated exploiting the equivalent spectrum transfer function of the cascade of WSSs. To confirm the goodness of these values, B_{-3dB} and f_c of the cases relating to the *Analytical feedback-based*

simulation set-up, have been also calulated exploiting power levels at the receiver after the retransmissio(third stage).
As shown in figure 3.34, the interpolation of power levels of each subcarrier permits us to obtain the equivalent transfer function of the WSS and so it is possible to estimate the -3 dB bandwidth and the central frequency, denoted as $\hat{B}_{-3dB}$ and $\hat{f}_c$ respectively. At this point we can compare these values with B_{-3dB} and f_c with the linear regression as shown in figures 3.44 and 3.45. The relationship between the two set is good and most of them fall close to the linear function(orange line). Similar results are obtained for the transmissions with the same symbol rate, in fact the bandwith of the spectrum of the WSS changes with the symbol rate.

Here the explanation of the legned of figures 3.35 - 3.42.
Simulation: Analytical optimized simulation set-up; **Theory**: Theoretical set-up; **Feedback**: Analytical feedback-based simulation set-up; **Optimized Theory**: Optimized analytical set-up.

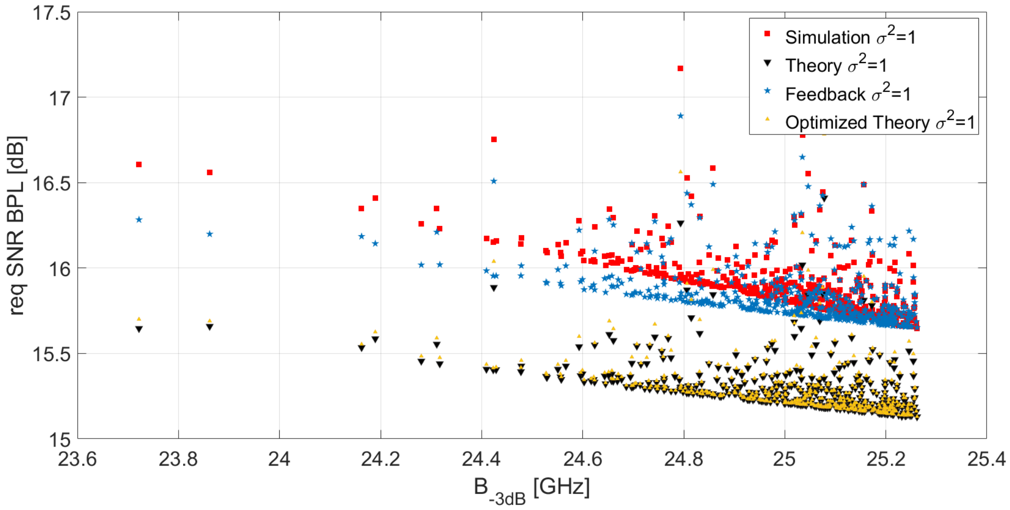


Figure 3.35: *Required SNR versus -3 dB bandwidth for a 200G transmission considering all seen set-ups with MSC configuration.*

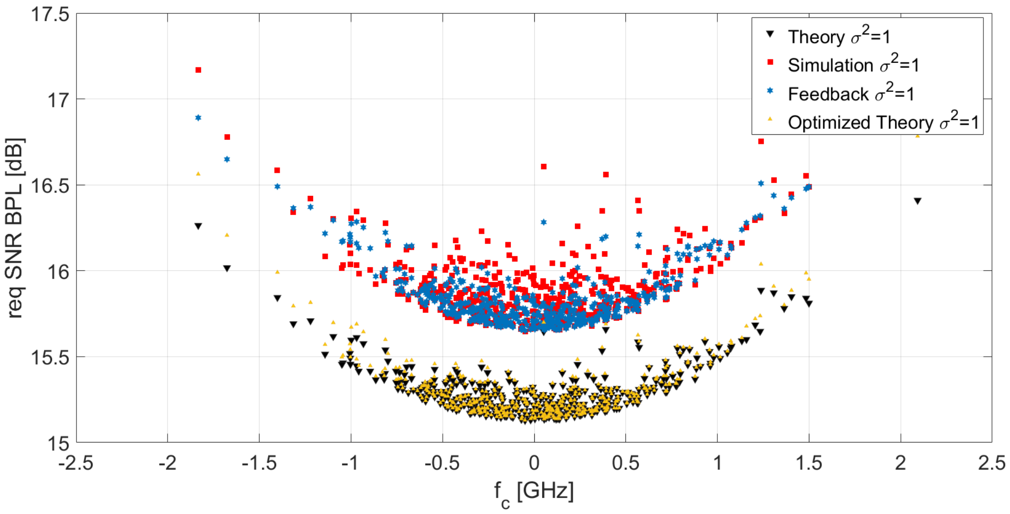


Figure 3.36: *Required SNR versus central frequency for a 200G transmission considering all seen set-ups with MSC configuration.*

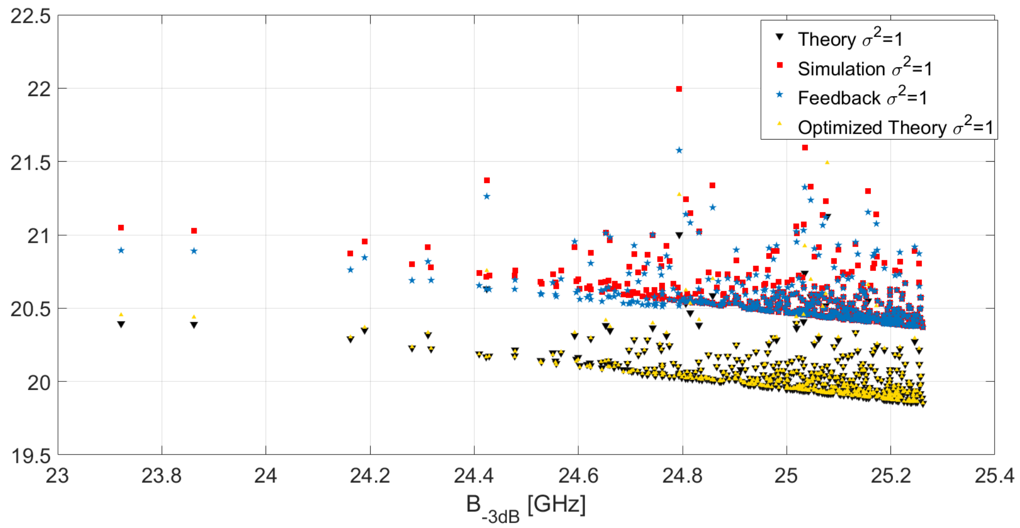


Figure 3.37: *Required SNR versus -3 dB bandwidth for a 300G transmission considering all seen set-ups with MSC configuration.*

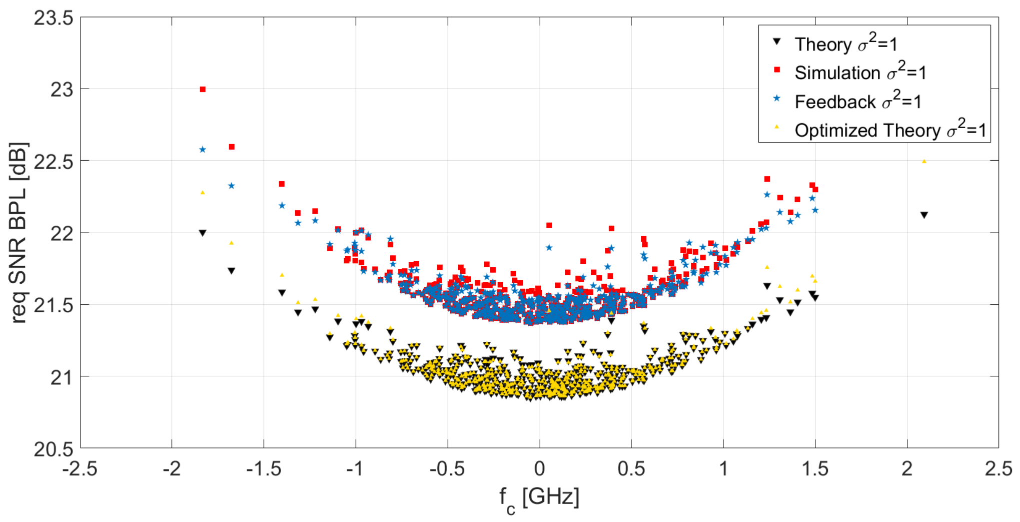


Figure 3.38: *Required SNR versus central frequency for a 300G transmission considering all seen set-ups with MSC configuration.*

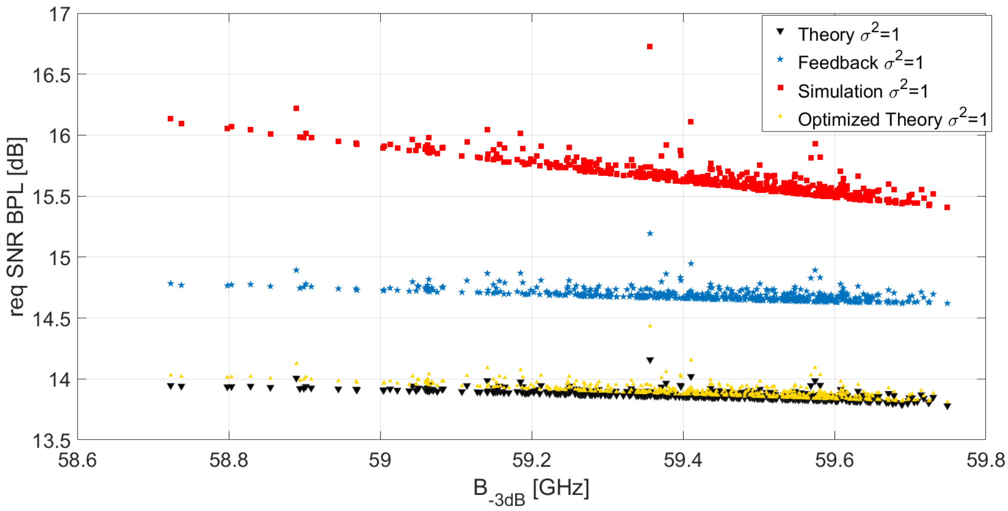


Figure 3.39: *Required SNR versus -3 dB bandwidth for a 400G transmission considering all seen set-ups with MSC configuration.*

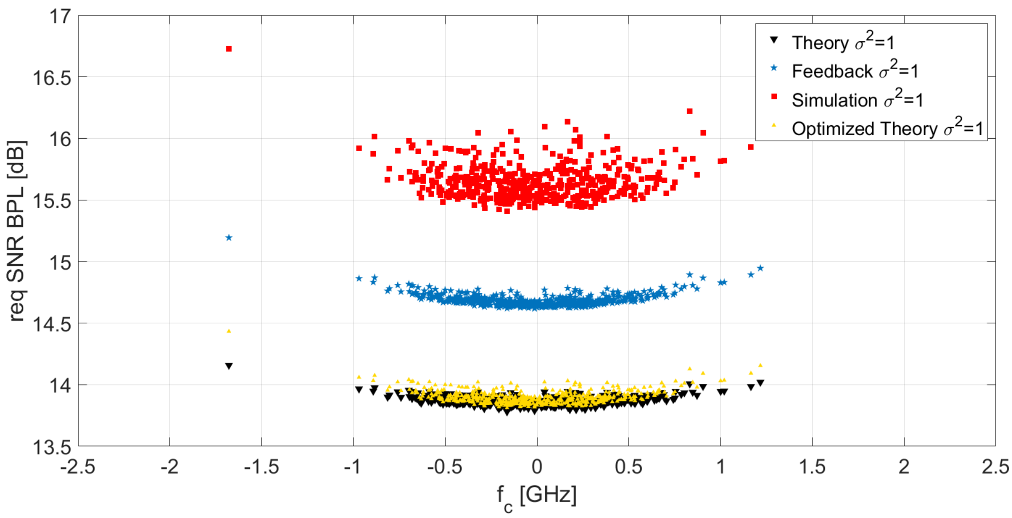


Figure 3.40: *Required SNR versus central frequency for a 400G transmission considering all seen set-ups with MSC configuration.*

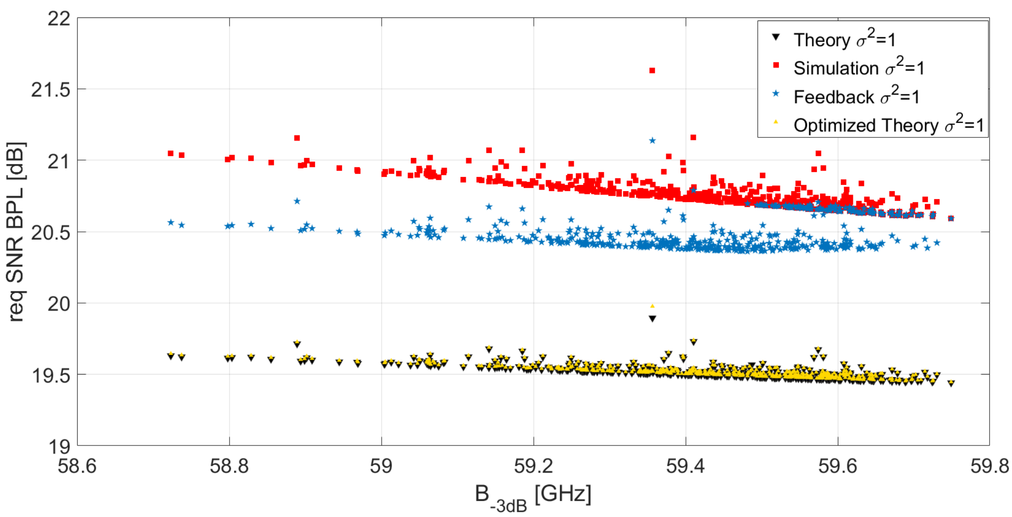


Figure 3.41: *Required SNR versus -3 dB bandwidth for a 600G transmission considering all seen set-ups with MSC configuration.*

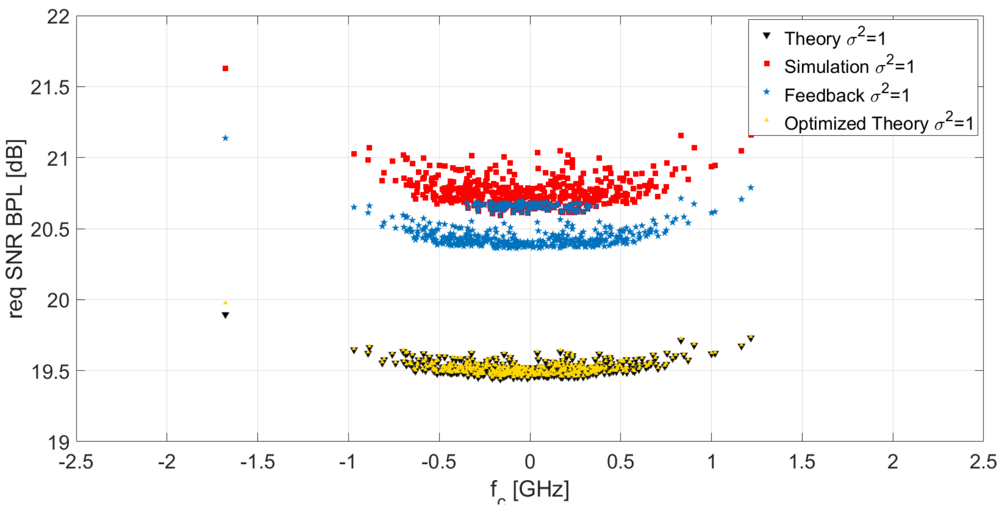
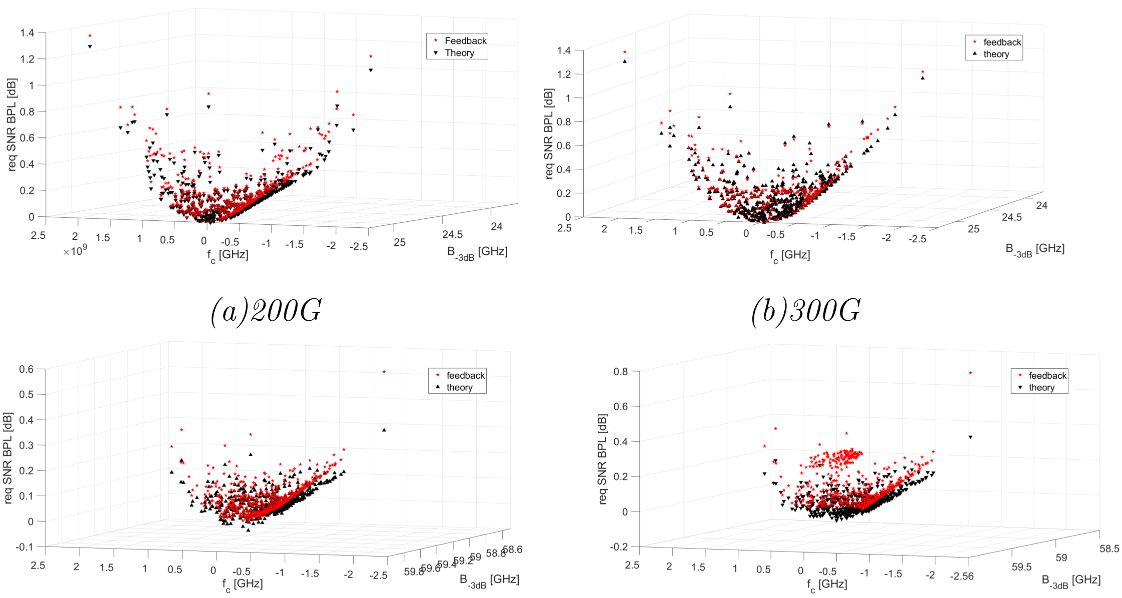


Figure 3.42: *Required SNR versus central frequency for a 600G transmission considering all seen set-ups with MSC configuration.*



(a)200G (b)300G

(c)400G (d)600G

Figure 3.43: *Overlap of surfaces relating to* Analytical feedback-based simulation *set-up and* Theory *in MSC mode for the four cases of the considered bit rate.*

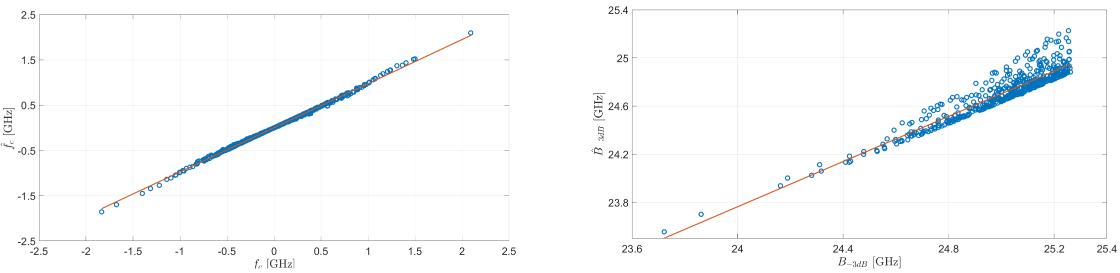


Figure 3.44: *Linear regression for central frequencies and -3dB bandwidth for 32 GBaud signal.*

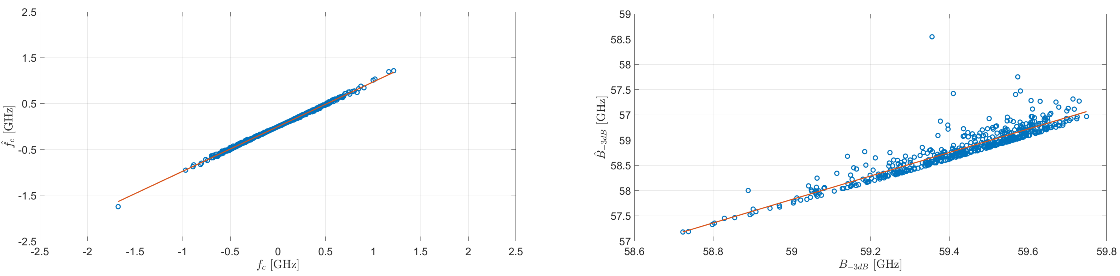


Figure 3.45: *Linear regression for central frequencies and -3dB bandwidth for 64 GBaud signal.*

From previous results we can make two important considerations: *Theory* and *Optimized Analytical* results are almost the same and then *Analytical feedback-based simulation* and *Theory* results define surfaces with similar characteristics as seen in figure 3.43. If up to now this consideration was done from a qualitative point of view, the next step is to fit the points of each surface in order to find a mathematical equation to define these surfaces. The fitting of each surface was done with the *Curve Fitting Tool* of MATLAB.
Fitted surfaces are defined by a second degree equation and shown in figure 3.46:

$$\mathrm{f(x,y) = p_{00} + p_{10}x + p_{01}y + p_{20}x^2 + p_{11}xy + p_{02}y^2} \tag{3.4}$$

There are some coefficients that are too small,therefore we can consider them negligible.The equation simplifies as:

$$\mathrm{f(x,y) = p_{00} + p_{10}x + p_{02}y^2} \tag{3.5}$$

Coefficient p_{10} defines the inclination of the surface,e.g. the steepness of the trend in B_{-3dB} vs required SNR plots, while coefficient p_{02} defines the aperture.

	200G		**300G**		**400G**		**600G**	
	Theory	**Feedback**	**Theory**	**Feedback**	**Theory**	**Feedback**	**Theory**	**Feedback**
p00	23.24	24.77	30.07	29.43	22.17	23.9	30.39	—
p10	-0.321	-0.361	-0.364	-0.318	-0.140	-0.155	-0.183	—
p20	0.303	0.368	0.301	0.355	0.115	0.198	0.150	—

Table 3.9: *Coefficients of surfaces of Theoretical and Analytical feedback-based simulation set-ups.*

	200G		**300G**		**400G**		**600G**	
	Opt. Theory	**Feedback**	**Opt. Theory**	**Feedback**	**Opt. Theory**	**Feedback**	**Opt. Theory**	**Feedback**
p00	23.99	24.77	30.41	29.43	26.57	23.9	30.78	—
p10	-0.306	-0.361	-0.378	-0.318	-0.214	-0.155	-0.190	—
p20	0.325	0.368	0.364	0.355	0.195	0.198	0.159	—

Table 3.10: *Coefficients of surfaces of Optimized Analytical and Analytical feedback-based simulation set-ups.*

In tables 3.9 and 3.10 the column of the *Analytical feedback-based simulation* case at 600G is empty because of the overmentioned bug and so it is impossible to define a surface as in other cases. The goodness of the fitting is good, in fact the Root Mean Square Error is low with values in the order of 10^{-2}. Comparing the values reported in tables 3.9 and 3.10, we can understand the dependence of the coefficients with repsect to the symbol rate, the bit rate and differences between *Theory*, *Optimized Analytical* and *Analytical feedback-based simulation* set-ups. Let us start oberving the cases with the same symbol rate and so comparing 200G with 300G and 400G with 600G. We can see that p_{10} and p_{02} are very similar because in these couples of cases all the subcarriers have the same symbol rate (2 GBaud for 200G and 300G, 4 Gbaud for 400G and 600G). This means that the required SNR has a similar variation when B_{-3dB} and f_c change. The difference is observed for coefficient p_{00} because of the different order of modulation formats per subcarrier. What we obtain is that the two compared paraboloid are shifted on the third dimension(required SNR). Another comparison can be done with repsect to transmission with the same modulation format per subcarrier before bit loading optimization, and so between 200G and 400G and between 300G and 600G. In both couples we can observe that p_{10} is aroud -0.3 for 200G and 300G while in 400G and 600G it is around -0.1. This means that when B_{-3dB} decreases there is an higher increase of the required SNR where the symbol rate per subcarrier is lower. The same thing happen for the coefficient p_{02} but here the discriminant is the increase of f_c value.

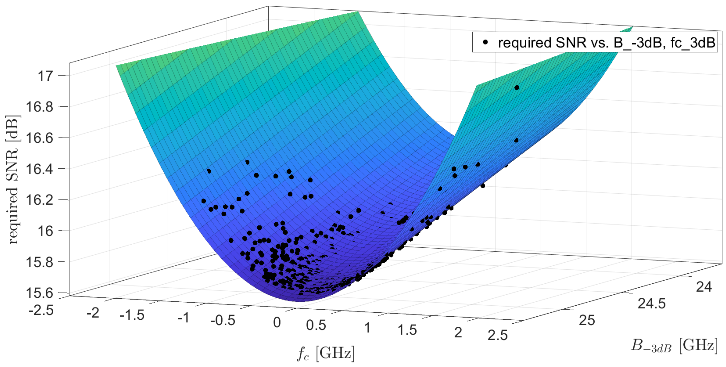


Figure 3.46: *Fitting of the surface.*

The last consideration is done observing the differences between the three set-ups with the same value of bit rate. We can say that *Theory* and *Optimized Analytical* set-ups give us very close results observing figures 3.35 - 3.42 and coefficients in table 3.10. If we make a comparison between *Theory* and *Analytical feedback-based simulation* set-ups we can say that p_{10} and p_{02} of the two cases are quite similar or marginally different to demonstrate what we can observe in figure 3.43 with the overlay of the surfaces. In addition to what is observed in figures 3.35 - 3.42, where for each case of bit-rate the penalty between *Theory*, *Optimized Analytical* set-up and *Analytical feedback-based simulation* set-up is practically constant for each of the 500 set of tested frequency offset. Considering these two points we can think to exploit such knowledge to estimate the required SNR given by *Analytical feedback-based simulation* system starting from a point on the "*Theory*" surface. Choosing a values B_{-3dB} and f_c we can obtain required SNR given by *Theory* and then applying the known penalty we obtain an estimate of the required SNR given by *Analytical feedback-based simulation* set-up with the same values of B_{-3dB} and f_c. The benefit of this method is to reproduce the relationship between B_{-3dB}, f_c and required SNR of the *Analytical feedback-based simulation* system starting from theoretical results saving time for simulations. Comparing the amount of time the simulator takes to give us these results for all 500 cases of frequency offset, if for theory it needs a couple of minutes, on the other hand the simulation of *Analytical feedback-based simulation* system takes about 2 days. We can understand that this method could be a huge advantage in this way. The calculation of B_{-3dB} and f_c can be done without a proper simulation but simply providing the set of frequency offset as input to the formula 3.3 which are very reliable considering what said about the linear regression. Naturally, at this point of this study it is important to say that to have a good reliability of this method, f_c must be in range of -0.5-0.5 GHz but just outside of this range we can do an estimation jus to have an idea of the required SNR given by the *Analytical feedback-based simulation* system considering a marginal error. This study can be completed analyzing a larger number of cases of number of subcarriers, number of cascaded WSS or different set-up so that this strategy can be used widely.

Chapter 4

Conclusions

The study reported in this thesis focused on multi-subcarrier transmission with the aim to observe deeply the effects of cascade ROADMs on the performances of the considered systems. Different signal configurations have been tested with different values of bit rate, passing form 200G up to higher values as 600G. In order to exploit all the advantages enabled by the use of multi-subcarrier signals, optimization strategies as bit and power loading were used so that the signal was configured as FDHMF.
The whole study was organized on different steps starting from a general investigation where, for each value of bit-rate different number of subcarriers and cascaded ROADMs have been tested in order to have an idea of the performances of an optical system composed of a transmitter and a receiver. From these results the main considerations were about the advantage of using the highest possible number of subcarriers applying optimization strategies. Based on the obtained results, only relevant cases were further analyzed in the following investigations. After this first step, we studied the effects of WSSs on a 16 subcarriers signal taking into account cases with symbol rate per subcarrier of 2 GBaud and 4 GBaud with 4 and 8 cascaded WSSs respectively.
Continuing the study on WSS, after having observed the impact of the filtering effect, also the insertion of frequency offset in the sepctrum of the WSS was analyzed. In preliminary studies, the frequency offset variations were done in a deterministic way observing that for values higher than 3 GHz the performances of the considered signal configurations were too low. Moving to more realistic scenarios the insertion of frequency offset was done in a randomic way also because in a network it is impossible to know the amount of frequency offset present after a cascade of ROADMs. Values of frequency offset were randomly extracted once with a variance between 0.5 GHz and 1 GHz and used to test different system set-ups measuring the

required SNR needed to reach a BER of $1.76 \cdot 10^{-2}$. First of all we obtained results from theoretical formulas were the power and bit optimizations were determined analytically. These results are very optimistic, considered as the lower bound for the required SNR and so they are assumed to be the reference for the evaluation of the results of the other set-ups.
The other two set-ups were based on two stages where after a bit and power loading theoretical optimization without frequency offset, the signal such modelled is exploited by the second stage. The second stage was considered in a first case a theoretical optical system as the previous one and then in the second case a proper optical system was considered performing a time-domain simulation. Results of this two set-ups were different: in the first case results were very similar to theoretical ones while in the second set-up, depending on the bit-rate the penalty was in the range of 0.8-1.5 dB of required SNR. A new set-up is then tested in order to reduce the required SNR penalty with respect to theory. The new system is based on a first flat power transmission, a feedback based on a theoretical bit and power loading optimization and then a second retransmission. For all the aforementioned set-ups, signals with a bit rate of 200G, 300G, 400G and 600G are tested for 500 different set of frequency offset. In this case the penalty is lower with values varying from 0.5 dB and 0.8 dB.
The next step is to calculate, for each set-up and bit-rate case, the B_{-3dB} and the f_c of the equivalent spectrum of the cascade of WSSs for each set of frequency offset. The set of the triplets of B_{-3dB}, f_c and required SNR define a parabolic surface in all the performed simulations. Making some comparisons we have seen that the surface defined by *Analytical feedback-based simulation* set-up can be shifted overlaying it on the surface defined by *Theoretical* set-up with good results because the penalty is quite constant. These qualitative consideration are confirmed fitting the surfaces in order to find the equation defining the parabolic surface.
Comparing surfaces of *Theoretical* and *Analytical feedback-based simulation* set-up we have seen that coefficients are quite similar excluding the constant term that is different because of the required SNR penalty that is a known value. All these considerations has led us to say that,knowning the penalty between two set-up and the relationship between B_{-3dB}, f_c and required SNR, we can estimate the required SNR related to the same values of B_{-3dB} and f_c of the second set-up. This method for the estimation of required SNR gives us an advantage in terms of time because, taking into account the statistical study in this thesis, to obtain theoretical results we need an amount of time that is 500 times lower with respect to the time needed to obtain results from the *Analytical feedback-based simulation* set-up. Naturally, before to apply this way of working,we need to have a preliminary study on the specific set-up finding proper ralationship to define surfaces. Over time, reusing

this model we can take a lot of advantages.
The resulting estimated required SNR is reliable for variations of f_c about 0.5 GHz and reduction of B_{-3dB} of about 0.4 GHz respect the value of B_{-3dB} without frequency offset. Out of these ranges the model may still be applied even if some inaccuracies could be present. Maybe a better study in this direction can be useful to improve relationship between two considered set-up. This work can be further extended to a broad range of cases in terms of number of subcarriers, symbol rate, bit rate or number of cascaded WSSs and for different set-ups.

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