POLITECNICO DI TORINO

Master degree course in Communications and Computer Networks Engineering

Master Degree Thesis

Optimization of Multi-Carrier Modulation Techniques for Spectral Efficient Transmission Under Strong Optical Filtering

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Academic year 2017-2018

Summary

This thesis has been developed under the guidance of Fernando Guiomar at Instituto de Telecomunicações (IT) in Aveiro, Portugal, a renowned research centre located inside the Campus of Santiago of University of Aveiro.

Due to the increasing demand of network capacity and need of a more flexible network, the use of Reconfigurable Optical Add-Drop Multiplexers (ROADMs), is mandatory. ROADMs are implemented using Wavelength Selective Switches (WSS), that are progressing mobile filters. Using a single-carrier modulation format, the signal, when passing through cascaded ROADMs, is more and more filtered, in particular at the edges of the frequency slot (bandwidth allocated to a WDM channel). To get better performances in terms of SNR, a preliminary study with simulation has been performed proposing multi subcarrier (MSC) modulation as an alternative to single-carrier modulation format. For this purpose, Frequency Division Hybrid Modulation Formats (FDHMFs) have also been considered, which consists in using a different modulation format per each subcarrier. Afterwards, experiments have been conducted in the laboratory of optical communications of IT Aveiro to validate simulation results.

Preliminary results were presented in the paper entitled "Reducing ROADM Filtering Penalties using Subcarrier Multiplexing with Offline Bit and Power Loading", which was submitted and accepted at the 44^{th} European Conference on Optical Communication, held in Rome, September 24-26, 2018.

Acknowledgements

Although I am not good with words in expressing my feelings, I would like to express my gratitude to all the people who helped me to write this thesis and to become the woman I am.

First of all, I would like to thank Instituto de Telecomunicaçoes of Aveiro, for having welcomed me and having given me the opportunity to work on my thesis there, and my internship supervisor Fernando Guiomar, who helped me a lot in developing this thesis and in growing as a researcher. Thanks to his encouraging words, I always regained confidence every time I felt disheartened and I understood the direction I would like to follow in my life. I also would like to express my gratitude to Abel Lorences-Riesgo, who provided me assistance in the laboratory, and to Professor Paulo Monteiro for his support.

A big thanks is for my parents, my sister and Tiziana, who always believed in me and always supported me, even when I was about to quit university. Without you I would never have been able to reach this important goal.

Thanks to my old friends Alessia, Elisa, Luca, Mattia, Alberto, Francesca, Giacomo and Andrea for all the years we spent together, and to my university friends Angelica, Carla, Claudia, Federico and Livia for all the school misadventures we faced together.

A special thanks to Anna, who supported me the most during my staying in Portugal. To all the people I met there and during these university years, you have my gratitude for having helped me in growing and becoming a better person.

Margareth

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Faber est suae quisque fortunae.
[C. A. Cieco]

Chapter 1

Introduction

1.1 Networks and communication systems

Telecommunication systems provide connections among users allowing communications when long distances are involved. The general scheme of a communication system is presented in Figure 1.1; it is composed of the transmitter (TX), the communication channel and the receiver (RX). At the input of the system there is a sequence of bits that the TX properly modulates into an analog signal *s(t)*. Afterwards, the analog signal is sent into the communication channel and is received with an additive noise *n(t)*. Thus, the received signal is

$$r(t) = s(t) + n(t) \tag{1.1}$$

which is still analogical. At the RX, *r(t)* is decoded to recover the original sequence of bits.

Figure 1.1: *Scheme of a communication system.*

A network is needed to connect different users and it is characterized by two types of entities: nodes and links. Nodes perform data processing, forwarding and routing, whereas links connect different nodes. Links can be free space, cables or optical fibers.

Communication channels can be point-to-point (singlecast), when only two nodes communicate with each other, or multicast (broadcast), when every node can communicate with other nodes (Figure 1.2).

In general, to fully exploit channel resources, they are shared through time, frequency, space or code division multiplexing and multiple access techniques. Multiplexing occurs when the channel is point-to-point, instead multiple access occurs in case of a broadcast channel. Depending on how nodes are placed and connected in the network, it is possible to define different network topologies: mesh, ring, bus, star, etc [1]. Some of them are depicted in Figure 1.3.

(a) Point-to-point channel *(b) Broadcast channel*

Figure 1.2: *Examples of point-to-point and broadcast channels.*

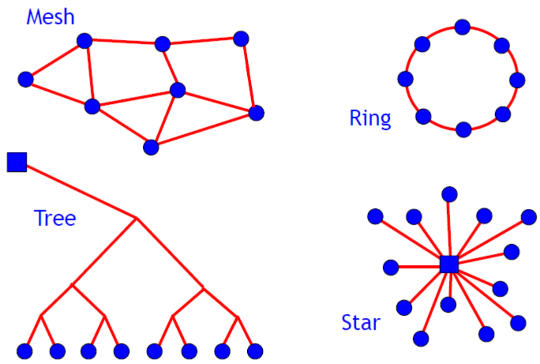


Figure 1.3: *Examples of network topologies (mostly used in optical networks).*

In this thesis only links are analysed and they are represented by optical fibers and Wavelength Division Multiplexing (WDM) (or Frequency Division Multiplexing - FDM) is used to share resources and wavelength routing (WR) is applied. An example is shown in Figure 1.4. Wavelength Selective Switch (WSS), depicted in Figure 1.5 and placed in network nodes, selects the proper output port for each incoming wavelength allowing wavelength multiplexing.

1.2 Optical fibers and optical communication systems

Optical fibers for communication systems are generally made of ultra-pure silica glass (SiO_2) and are characterized by two main concentric sections: *core*, whose diameter is approximately 8-10 μm for high performance fibers, and *cladding*, whose diameter is 125 μm. The core contains also other materials inside, like Germanium, to make its refractive index n_{co} higher than the refractive index of the cladding n_{cl} ($n_{co} > n_{cl}$). As a consequence, light is confined and propagates only in the core and this is enough to prevent the light (electromagnetic field) from spreading outside the fiber [3][4]. Other external layers are added to protect the fiber from mechanical shock and damage, as shown in Figure 1.6, in the right-side picture.

Moreover, optical fibers can be classified according to the nature of their boundary into *step index* and *graded index* fibers and according to the number of propagated modes, into *single-mode* (SMF) and *multi-mode* (MMF) fibers. Single-mode fibers propagate only one mode, their core diameter is about 10 μm and they are the commonly used optical fibers for long-haul systems.

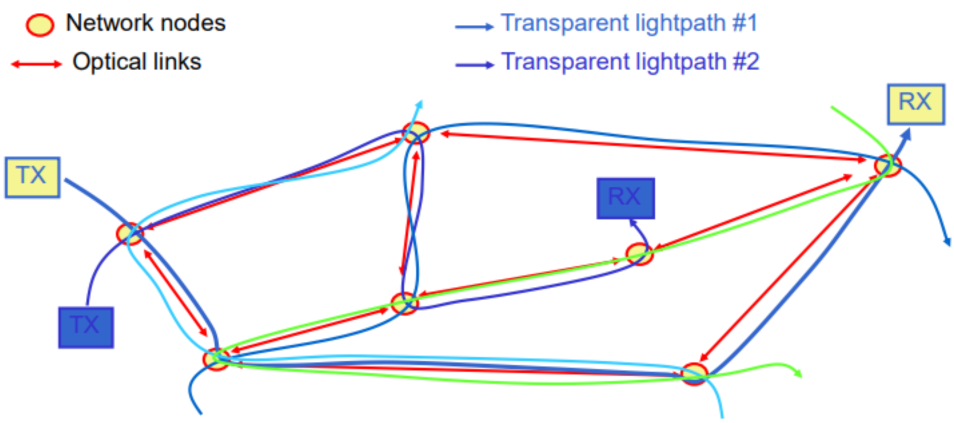


Figure 1.4: *Example of Wavelength Routing [1]: each color represents a wavelength.*

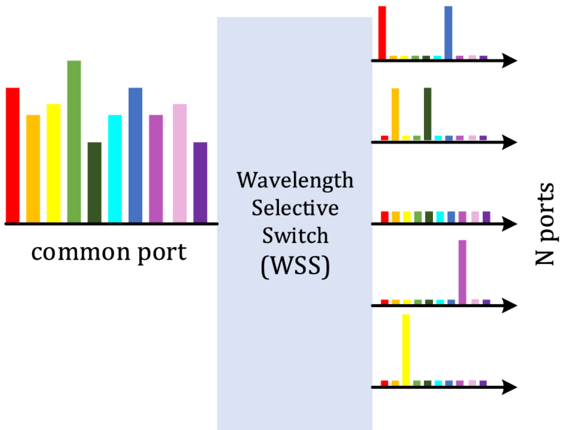


Figure 1.5: *Wavelength Selective Switch (WSS) [2].*

In general, for telecommunication applications at 1550 nm single-mode fibers are used, since they have the lowest possible attenuation (around 0.2 dB/km). Commercial standard for 1550 nm telecommunication fibers are shown in Table 1.1.

Among all types of physical links, optical fibers are characterized by the lowest attenuations ($< 0.2\,dB/km$), resulting in the best choice when long distances are involved. Fiber attenuation assumes different values depending on the central wavelength (frequency) and three optical windows can be recognized around the lowest attenuations. In Figure 1.7, spectral occupation for each of them is shown with respect to wavelength:

- 1^{st} *window*, around 980 nm;
- 2^{nd} *window*, around 1300 nm, it is also called *O-band*;
- 3^{rd} *window*, called *C-band*, is defined between 1530 and 1570 nm (191-196 THz). It is also the frequency range for which the best optical amplifiers can be built. Top-level performance systems work in this window, because attenuations are lower than

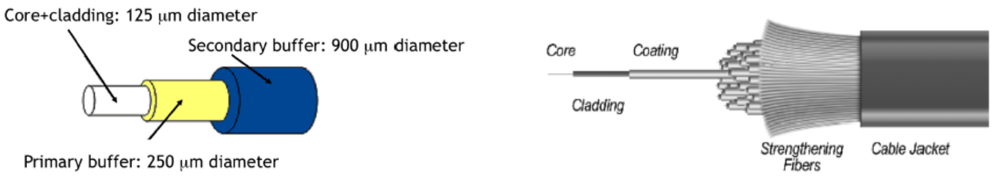


Figure 1.6: *Structure of an optical fiber cable.*

Type	ITU.T
Conventional SMF	G.652
Dispersion shifted SMF	G.653
Cut-off shifted (low attenuation) SMF	G.654
Non zero dispersion (NZD) shifted SMF	G.655
Low dispersion slope Non-zero Dispersion Shifted SMF	G.656

Table 1.1: *Commercial standard for telecommunication fibers [3].*

$2\,dB/Km$.

To reach long distances, transmitted power should be increased and low attenuation fibers should be used. Unfortunately, transmitted power cannot be increased too much because of non-linearity effects like the Kerr effect, the most prominent one that causes the variation in the glass refractive index as a function of the input power. The variation in the refractive index produces a shift in phase and the higher the input power, the higher the refractive index variation. Therefore, when very long distances are involved, the transmitted signal must be periodically amplified.

Depending on the presence or not of optical amplification, three classes of optical transmission systems can be defined:

1. Single-span, non-optically amplified system;
2. Single-span, optically amplified system;
3. Multi-span, optically amplified system.

A pictorial representation is reported in Figure 1.8.

Amplification is necessary to recover the transmitted signal from fiber losses due to attenuation along the fiber. In particular, optical amplification is the commonly used technology, since it allows to amplify the signal without moving to/from electrical domain. In fact, in the past, an optical-electrical-optical (OEO) conversion was required, because signal amplification was possible only in the electrical domain. Nowadays, three possible solutions are available in case of optical amplification [4]:

- *Semiconductor Optical Amplifier (SOA)*, which amplifies the input signal through stimulated emission. The working principle is the same as semiconductor lasers, for which a photon with a suitable energy is pumped through an injected current to

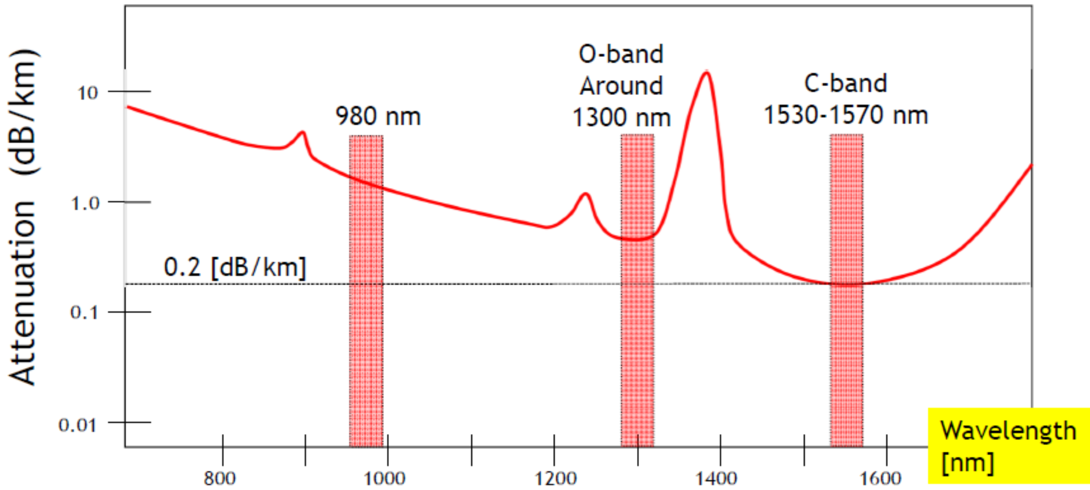


Figure 1.7: *Fiber attenuation (dB/km) as a function of wavelength (nm) [4].*

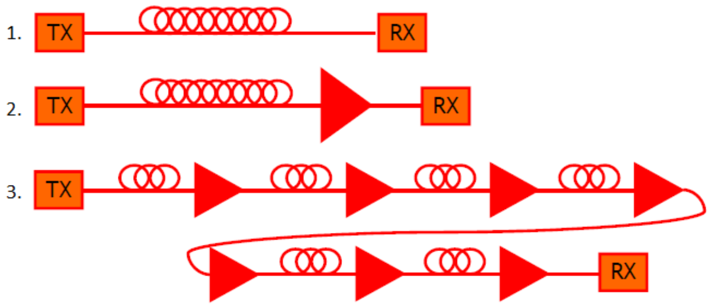


Figure 1.8: *Three classes of optical transmission systems. From top to bottom: single-span non optically amplified system (1), single-span optically amplified system (2) and multi-span optically amplified system (3).*

stimulate the emission of another photon, providing amplification. In practice they are no longer used;

- *Erbium Doped Fiber Amplifier (EDFA)*, similar to SOA, but in this case the amplification is performed by injecting a pump laser into a short piece of fiber whose core is doped with Erbium ions (Er^{3+}). The presence of these ions guarantees the amplification instead of attenuation. In fact, the pumped laser excites also these ions, which move to a higher state of energy. Once they are hit by incoming signal photons, erbium ions release part of their energy as photons, allowing amplification, and return to a lower state of energy;

- *Raman amplifiers*, which exploit stimulated Raman scattering in the transmission fiber to have distributed amplification.

In this thesis, the system considered (Figure 1.9) is a multi-span optically amplified system, where more than one span and optical amplifier are present and ROAMDs (WSS) are placed between links. Amplification is performed using EDFAs.

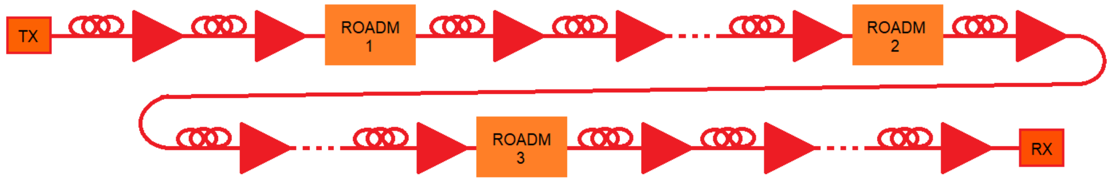


Figure 1.9: *Multi-span optical amplified system using EDFAs and ROAMDs.*

Optical fibers carry two independent electrical fields that travel onto orthogonal polarizations ($\hat{x}$ and $\hat{y}$ polarizations), thus the light in the optical fiber is

$$\vec{E} = [E_{Ix}(t) + jE_{Qx}]\hat{x} + [E_{Iy}(t) + jE_{Qy}]\hat{y} \tag{1.2}$$

where $E_{Ix}(t) + jE_{Qx}$ and $E_{Iy}(t) + jE_{Qy}$ are complex numbers, each of them composed by in-phase (I) and quadrature (Q) components. A pictorial representation is shown in Figure 1.10. This fiber characteristic can be exploited to double the capacity through

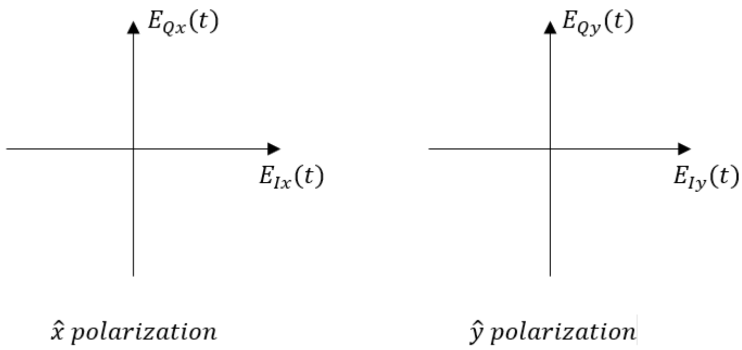


Figure 1.10: *Electric field components carried by an optical fiber.*

Polarization Multiplexing (PM), that allows to transmit two different signals over the two independent polarizations. Therefore, more complex modulation formats of the type PM-2^N Quadrature Amplitude Modulation (QAM), N being an integer number, can be used (Figure 1.11). Figure 1.12 shows the modulator structure at the transmitter side. To correctly demodulate complex signals at the receiver side, coherent receivers are used. The front-end is depicted in Figure 1.13. To extract all the four components of the received electric field $\vec{E}_{ph}(t)$, an external signal called *local oscillator* ($\vec{E}_{LO}$) is added. To detect one of the four components, the local oscillator should be aligned with that component and should have the same frequency. Once the transmitted sequence is received, the receiver applies a decoding algorithm able to make a decision about each received bit.

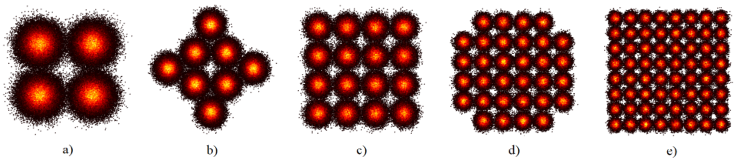


Figure 1.11: *QAM moduation formats considered in this thesis: a) QPSK, b) cross 8QAM, c) square 16QAM, d) cross 32QAM and e) square 64QAM [9].*

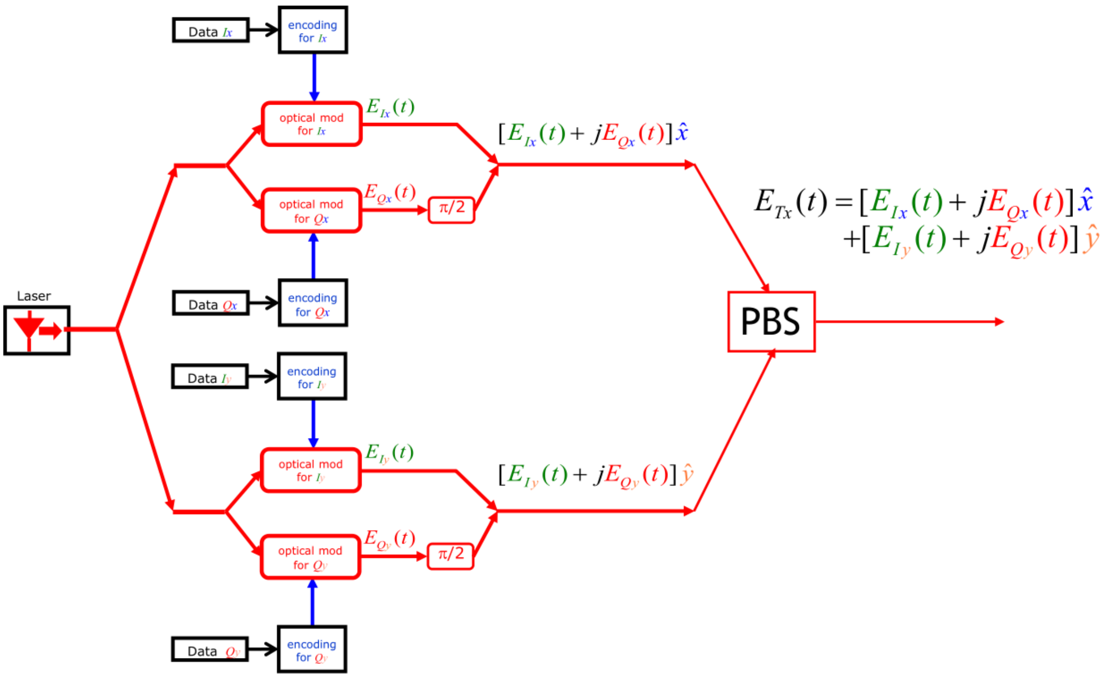


Figure 1.12: *Modulator structure. PBS stands for Polarizing Beam Splitter.*

1.3 Purpose and organization of the thesis

Nowadays internet data traffic is continuously growing especially due to an increase of multimedia contents, services and applications available on the network. Moreover, incoming 5G requirements in terms of bandwidth, latency (below 1 ms) and reliability [5], imply a major upgrade on currently deployed networks, in which optical fiber communication will have a key role. Therefore, new generation networks must guarantee more capacity and at the same time they should be more flexible.

Optical fibers are the best solution to provide huge capacity, whereas flexibility is provided by Reconfigurable Optical Add-Drop Multiplexers (ROADMS), which allow to switch traffic in a remotely way through a Wavelength Selective Switching (WSS) module [7]. The main problem is that WSS are not ideal filters because the shape of their transfer funcation is not a perfect rectangle in frequency. Thus, if they are present in a large number, the signal experiences strong filtering and very low SNR, in particular at the edges of the

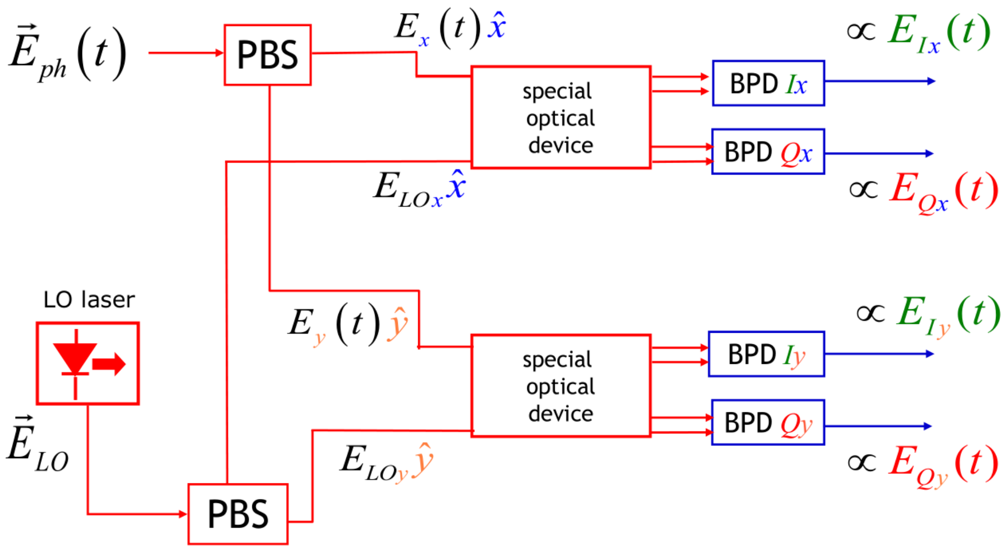


Figure 1.13: *Coherent receiver front-end. PBS stands for Polarizing Beam Splitter and BPD stands for Balanced Photo Detector.*

frequency frame.

Nonlinear effects are second-order effects, therefore, for simplicity, they are not taken into account in system analysis. The link is emulated in linearity, thus only accumulation of Amplified Spontaneous Emission (ASE) noise at the receiver and WSS filters are considered. Given 200G rate constraint and several cascaded ROADMs over the link, the aim is to find the best modulation such that performance is maximized.

To get better performance, Forward Error Correction (FEC) technique is implemented to detect and correct errors at the receiver. The original sequence of k bits is converted into a codeword of n bits by adding $n-k$ redundant bits at the encoding stage before trasmission. Thus, the ratio

$$OH = \frac{n-k}{k} \tag{1.3}$$

is called *overhead* (OH) and affects the net bit rate. In fact, given a fixed net rate, the raw rate increases. As instance, given 200G net rate and 0.28 total overhead , the raw rate is 256G. FEC can be classified in: Soft Decision FEC (SD-FEC) and Hard Decision FEC (HD-FEC), which are characterized by different OH and different maximum pre-FEC BER to enable error-free post-FEC BER.

The thesis is divided into five chapters: Chapter 1 presents concepts of networks and optical communication systems, Chapter 2 contains the state-of-the-art and theoretical backgrounds about multi subcarrier modulations, Chapter 3 shows simulation results, Chapter 4 presents experimental results, and Chapters 5 is dedicated to conclusions.

Chapter 2

Theoretical background

2.1 Current scenario

Optical communication systems and optical fibers represent the higher growing physical layer technology in telecommunication field: they can carry very high data rates because of their very broad band (approximately 5 THz).

Nowadays, the increase of internet data consumption leads to a growth in network capacity demand, but this should be provided without replacing the infrastructure already in use. Besides large capacities, flexible bit rates are required as well. To perform wavelength routing and provide a flexible network, Reconfigurable Optical Add-Drop Multiplexers with Wavelength Selective Switchs are used, which, unfortunately, are responsible of filtering effects on the trasmitted signal. As presented and demonstrated in [8], the band-pass spectral response of a WSS is given by the convolution between the WSS aperture and the Gaussian shaped Optical Transfer Function (OTF) with standard deviation $\sigma = BW_{OTF}/(2\sqrt{2ln2})$, where BW_{OTF} is the 3 dB bandwidth. The resulting expression for the transfer function is

$$S(f) = \left[\frac{\sigma\sqrt{2\pi}}{2}\left[erf\left(\frac{B/2-f}{\sqrt{2}\sigma}\right) - erf\left(\frac{-B/2-f}{\sqrt{2}\sigma}\right)\right]\right]^{N_{WSS}} \tag{2.1}$$

where B is the bandwith of the frequency slot in which the WSS is placed and N_{WSS} is the number of cascaded WSS. Examples of transfer functions for an increasing number of cascaded WSS, $N_{WSS} \in \{0, \ldots, 7\}$, are shown in Figure 2.1. They are obtained for $B = 37.5\ GHz$ and $B_{OTF} = 10.4\ GHz$. It is easy to see that, by increasing the number of cascaded WSS, the available bandwidth decreases and the transfer function becomes narrower, inducing stronger filtering effects on the trasmitted signal.

Spectral efficiency (SE) measures how efficiently the available bandwidth is used and it is defined as the ratio between the net rate and the bandwidth. It can be maximized by exploiting the flex-grid concept, which consists in filling the entire bandwidth available by optimally allocating optical channels over frequency. To maximize bandwidth utilisation and provide higher network capacity, channel spacing should be very tight, but the combination of this tight channel spacing and filtering effects generates inter-symbol interference (ISI), resulting in a degradation of performance.

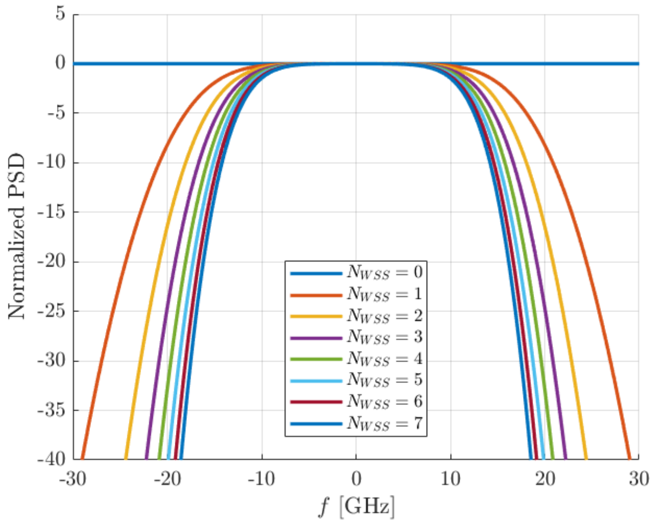


Figure 2.1: *Transfer functions of WSS for $N_{WSS} \in \{0, \ldots, 7\}$ cascaded units given by expression 2.1, where $B = 37.5$ GHz and $B_{OTF} = 10.4$ GHz.*

2.2 Single-carrier and multi-subcarrier modulations

To provide high network capacity and implement a flexible network, the optical transceiver can choose between two paradigms: single-carrier modulation and multi-subcarrier modulation [9].

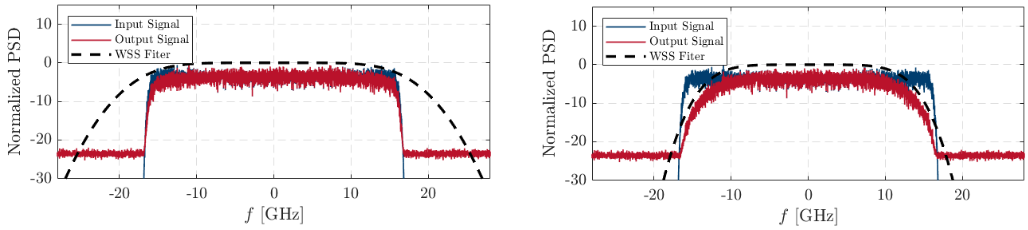
2.2.1 Single-carrier modulation

Current optical transceivers are based on single-carrier modulation, for which higher network capacity can be obtained by increasing the modulation format of the type PM-2^MQAM, where M is an integer number. Unfortunately, this signal is not immune to filtering effects due to cascaded WSS. Figure 2.2 shows an example of these effects on a 32 GBaud single-carrier signal, which is filtered by the transfer function of 1 WSS on the left, and by the transfer function of 5 WSS on the right. Transfer functions are computed from expression 2.1, with same values of B and B_{OTF} set in section 2.1. It is important to highlight that these filtering effects are independent from modulation formats. Instead, penalty changes being higher for higher order QAM formats.

As expected, output signal is more filtered when 5 WSS are present in cascade than when there is only 1 WSS. The effect is stronger at the edges of signal bandwidth, due to the narrower shape of the transfer function, resulting in a lower quality of the received signal.

2.2.2 Multi-subcarrier modulation

An alternative to single-carrier modulation is multi-subcarrier modulation, for which two main solutions have been proposed to provide flexible bit-rates: Orthogonal Frequency



(a) 1 WSS (b) 5 WSS

Figure 2.2: *Example of filtering effects on a 32 GBaud single-carrier signal due to the transfer function of cascaded WSS given by expression 2.1.*

Division Multiplexing (OFDM) and electronic Sub-Carrier Multiplexing (SCM). Mostly used in wireless communication, OFDM has been investigated to be used in coherent optical communication as well. Despite some advantages, it presents some limitations due to its high peak-to-average power-ratio (PAPR), which are: more stringent digital-to-analog (DAC) and analog-to-digital (ADC) conversion requirements and enhanced non-linear interference during signal propagation in fiber.

Compared to OFDM, subcarrier multiplexing uses few carriers (with a symbol rate of 2-4 GBaud), therefore it is more resilient to non-linear propagation impairments, such that submarine transmission over 10,500 km has been achieved [10]. The entire band of the SCM signal is composed of N_{SC} subcarriers (SCs), whose symbol-rate is the total symbol-rate divided by the number of subcarriers (N_{SC}). Each subcarrier can be assigned a different modulation format, leading to the concept of Frequency-Domain Hybrid Modulation Formats (FDHMF) [9]. The concept of SCM is depicted in Figure 2.3, with a particular emphasis on FDHMF.

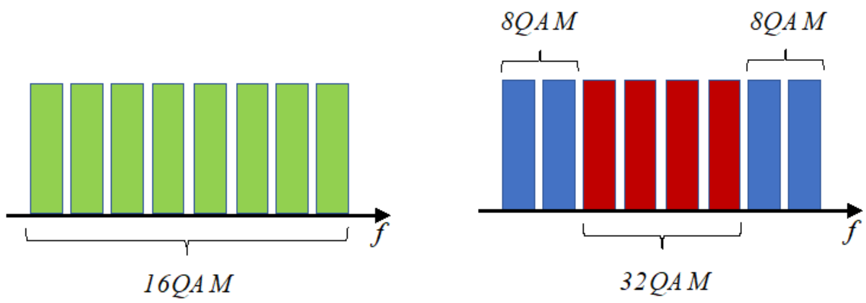
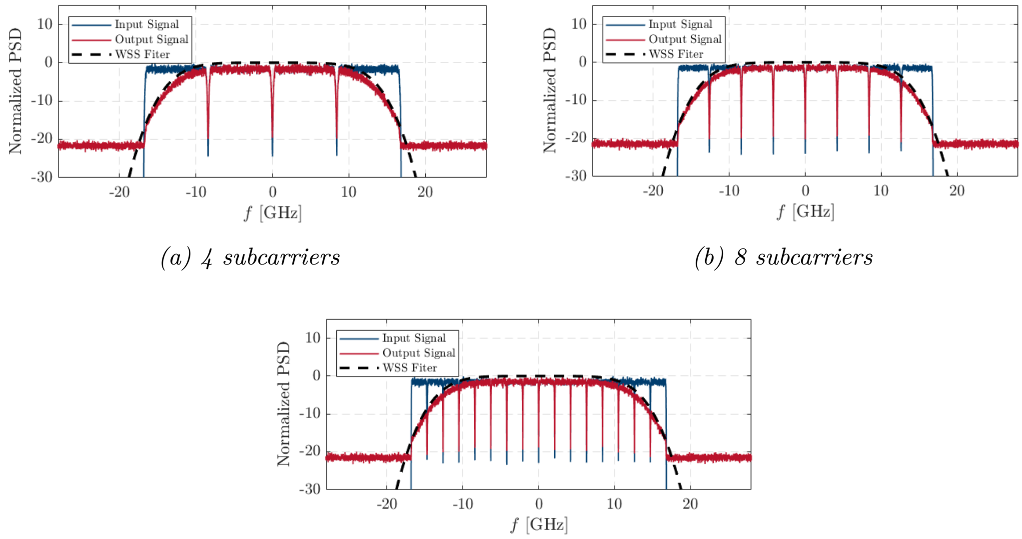


Figure 2.3: *Example of Sub-Carrier Multiplexing for signals multiplexed over 8 subcarriers with a particular emphasis on Frequency-Domain Hybrid Modulation Format (on the right).*

When N_{SC} is large, the band of each subcarrier is narrower, thus the increased granularity can fight against filtering effects due to cascaded Reconfigurable Optical Add-Drop Multiplexers (ROADMs). For instance, assuming a 200G total net bit-rate and that the signal transmitted on each subcarrier is modulated using 16QAM, Figure 2.4 shows the filtering effects on the spectrum of the trasmitted signal.



(a) 4 subcarriers

(b) 8 subcarriers

(c) 16 subcarriers

Figure 2.4: *Effects of a ROADM transfer function (5 cascaded) on the spectrum of a) 4x8 GBaud, b) 8x4 GBaud and c) 16x2 GBaud SCM signals.*

Mitigation of filtering effects can also be obtained by using low-order QAM modulation formats on subcarriers at the edges of the frequency frame [11]. In fact, lower order QAM constellations are more robust to channel impairments, such as filtering effects, than higher order constellations, which instead deliver more symbols. Therefore, since central subcarriers are not affected by filtering, it is better to use them for higher order QAM modulation formats.

2.3 Performance evaluation and improvements for multi-subcarrier modulation

At the receiver, the signal is received with a certain power level, which, in general, is lower than the power level of the transmitted signal, because of link attenuations and filtering. The main parameter used to evaluate the quality of the signal is the Signal to Noise Ratio (SNR), defined as the ratio between the signal power and the noise power measured over the bandwidth of each subcarrier. Another parameter is the Bit Error Rate (BER), which is the ratio between wrongly received bits and transmitted bits.

When multi subcarrier modulation is applied, the total transmitted power P is divided among all the subcarriers, therefore each of them is characterized by a power ratio (PR)

$$PR_k = \frac{P_{SC,k}}{P} \tag{2.2}$$

where $P_{SC,k}$ is the power of the k-th subcarrier and $P = \sum_{k=1}^{N_{SC}} P_{SC,k}$ the average power. In case of a FDHMF signal, each subcarrier can be characterized by a different power ratio, as shown in Figure 2.5.

Performance in each subcarrier can be analysed independently through the evaluation of SNR and BER per subcarrier, respectively defined as

$$SNR_{SC,k} = PR_K SNR \tag{2.3}$$

$$BER_{SC,k} = \Psi(SNR_{SC_k}, M_k). \tag{2.4}$$

In formula 2.4, Ψ is a non-linear function that depends on the constellation geometry and M_k is the size of the constellation transmitted on the k-th subcarrier.

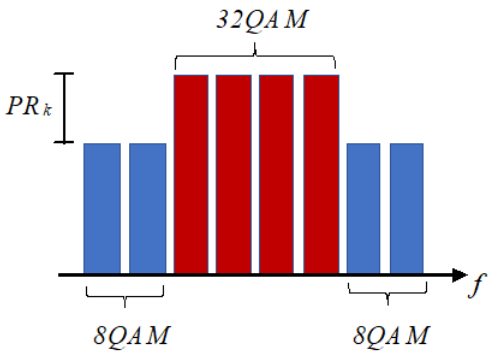


Figure 2.5: *Example of different power ratios for a 8 subcarriers FDHMF signal.*

For a SCM signal, performance degradation due to ROADMs filtering can be mitigated by adjusting the power ratios and constellations, therefore, depending on the approach, different power ratio strategies can be used [12][13]:

- *Same Power strategy*: all subcarriers are characterized by the same power, thus $PR_k = 0$ dB;
- *Minimum BER strategy*: it allows to find the optimum SNR that minimizes the estimated SNR for each subcarrier;
- *Water Filling strategy*: it gives more power to those subcarriers experiencing higher SNR;
- *Power Loading strategy (PL)*: the power of each subcarrier is manipulated without changing modulation format;
- *Bit Loading strategy (BL)*: it finds the best modulation format for each subcarrier keeping the same power;
- *Bit Loading and Water Filling strategy (BL & WF)*: for each subcarrier, it independently finds the optimal modulation format and, according to the experienced SNR, it provides the proper amount of power;

- *Bit and Power Loading strategy (BPL)*: for each subcarrier, modulation format and power level are independently adjusted.

Through simulations it is possible to study system behaviour when these strategies are applied in order to understand which of them provide the best performance.

Chapter 3

Simulation results

Simulations were performed using MATLAB software and OptDSP library to study system performance when the number of cascaded WSS varies from 0 to 7. Two types of simulations are considered: *simulation with theoretical power ratios* and *simulation with optimized power ratios*. The first one uses power ratios analytically computed based on theory, the second one performs an optimization during simulation to find the best power ratio values, such that SNRs are minimized. For each of them, two types of noise insertion and two types of WSS filtering are considered. Noise can be: *lumped noise at receiver side* and *equally distributed noise*. Whereas, WSS filter can be: *actual WSS filter* and *approximated WSS filter*.

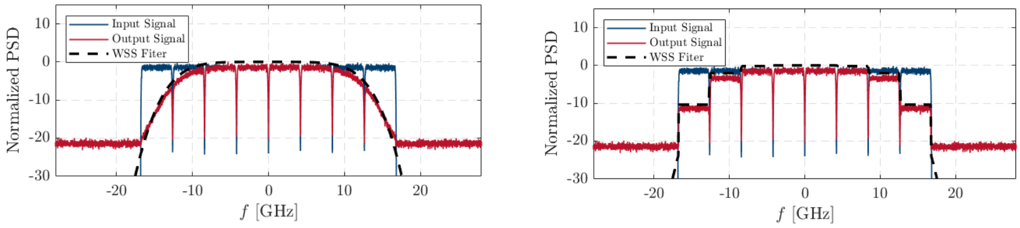
3.0.1 Types of WSS filters

The *actual WSS filter* transfer function is the one given by analytical expression 2.1, with $B = 37.5\ GHz$ and $B_{OTF} = 10.4\ GHz$, and it corresponds to a real filter. It is important to point out that the contributions to the effects responsible of performance degradation are two: average SNR loss per subcarrier and Inter-Symbol Interference (ISI) due to new flat filtering in a subcarrier, whose mitigation is achieved by performing digital equalization. At the receiver, by considering only average SNR, obtained by averaging over SNRs experienced by all the subcarriers, and assuming ideal compensation of filtering effects, the *actual WSS filter* model can be simplified into an *approximated WSS filter* [14]. In particular, this consists in taking the average value of the WSS transfer function within the bandwidth of each subcarrier, which gives the average signal attenuation caused by the WSS filter on each subcarrier. The effects of the transfer functions of these two different WSS filters on the input signal are shown in Figure 3.1.

Simulations with the approximated WSS filter simulate the theoretical behaviour of the system, so it is possible to refer to this case as the theory.

3.0.2 Noise insertion in simulations

As already presented above, two noise insertion models are considered. *Lumped noise at the receiver side* means that all WSS filters are matched in a single filter and a receiver-end lumped noise source is added afterwards. Therefore, the WSS filtering only affects the



(a) Actual/real WSS filter *(b) Approximated WSS filter*

Figure 3.1: *Effects of the transfer functions of (a) a real WSS filter and of (b) the approximated WSS filter on an 8x4 GBaud SCM input signal after 7 cascaded WSS.*

signal and does not remove any noise, thus being a worst case scenario. In case of *equally distributed noise*, the total amount of noise is divided into N_{WSS} equal portions and after each WSS, $1/N_{WSS}$ part of the total noise is added.

3.0.3 Types of time-domain simulations

The first type of simulation performed is the one using theoretical power ratios, which are analytically computed based on theory. Thus, power loading and bit loading are fully handled by the theory using the approximated WSS filters. Because of this approach, these simulations are not optimal, due to the approximations that have been performed in the derivation of the theory. For this reason, time-domain simulation based on optimized power ratios is needed, because the power loading is optimized using the *fminsearch* algorithm provided by MATLAB. This is a kind of brute-force approach, in which an initial solution (usually a flat power ratio for a given FDHMF configuration) is used to start the optimization process. Each subcarrier may be characterized by a different BER, so an average BER for the FDHMF signal is computed by averging over all the subcarriers. Then, based on the actual BER performance obtained from each iteration of the simulation, an optimized power ratio is found to minimize the average BER of the FDHMF signal, using this *fminsearch* function, which is basically a non-linear programming solver.

3.0.4 Forward Error Correction

To obtain better performance Forward Error Correction (FEC) technique is implemented. Depending on the selected type (SD-FEC or HD-FEC), their parameters assume different values, as reported in Table 3.1. In case of multi-subcarrier modulation, each subcarrier does not apply a different FEC. In fact, the FEC is assumed to be single and shared by all subcarriers by hypothesis, therefore, the target BER must be reached by the average BER of all subcarriers.

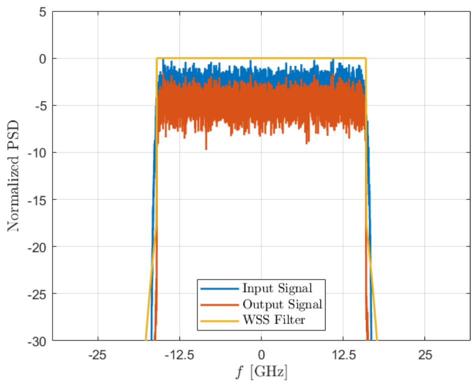
	SD-FEC	**HD-FEC**
Symbol Rate MSC [Baud]	$32 \cdot 10^9$	$28 \cdot 10^9$
FEC overhead	0.2	0.07
Total overhead	0.28	0.12
Target BER	$2 \cdot 10^{-2}$	$3.8 \cdot 10^{-3}$

Table 3.1: *Values of the parameters characterizing SD-FEC and HD-FEC.*

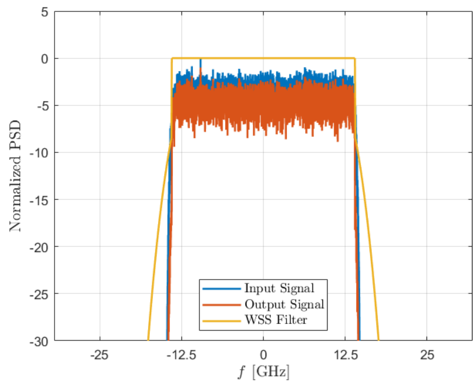
3.1 Single-carrier modulation without frequency offset

The most common form of modulation for 200G systems is a single carrier 32 GBaud PM-16QAM signal. In this case, it is not possible to apply power-ratio strategies presented in section 2.3.

In case of lumped noise at the receiver and single-carrier signal, the effects of the two types of filtering are shown in Figures 3.2 and 3.3. From them it is possible to see that, due to the shape of the transfer function of the actual WSS filter and after 7 cascaded WSS, frequencies of output signal at the edges of the available bandwidth are strongly filtered compared to those of input signal, as already seen according to theory. Therefore, to reach the target BER, a higher SNR is required. These considerations on the output signal lead to look for a more convenient solution able to minimize these filtering effects.



(a) SD-FEC

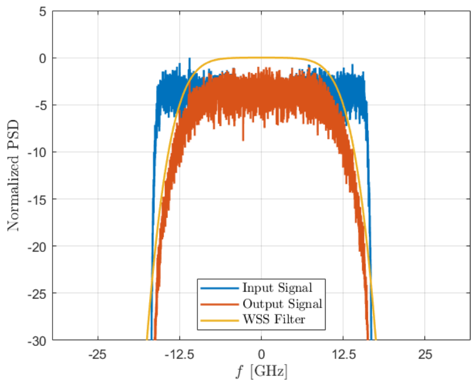


(b) HD-FEC

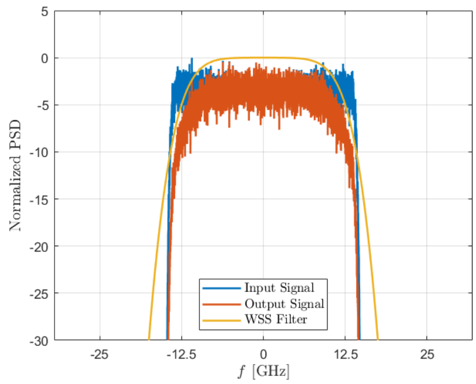
Figure 3.2: *ROADM transfer function (7 WSS) for a 32 GBaud single-carrier PM-16QAM signal with approximated WSS filter using SD-FEC and HD-FEC, respectively from left to right, and its effects on the input signal spectrum.*

In Figure 3.4 it is possible to see the behaviour of the required SNR in case of lumped noise at the receiver and single-carrier versus an increasing number of cascaded WSS.

Curves related to actual WSS filtering without equalization present a very high penalty, in particular when SD-FEC is applied. In fact, for the orange curve, already after 2 WSS,



(a) SD-FEC



(b) HD-FEC

Figure 3.3: *ROADM transfer function (7 WSS) for a 32 GBaud single-carrier PM-16QAM signal with actual WSS filter using SD-FEC and HD-FEC, respectively from left to right, and its effects on the input signal spectrum.*

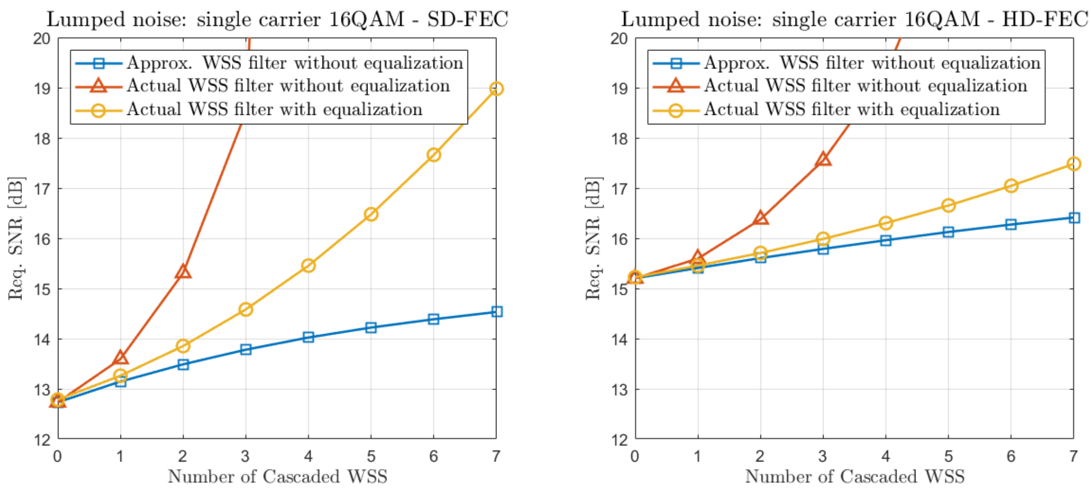


Figure 3.4: *Required SNR vs Number of Cascaded WSS for lumped noise at the receiver in case of 32 GBaud PM-16QAM single-carrier signal and both SD-FEC and HD-FEC for approximated WSS filter without equalization, actual WSS filter without equalization and actual WSS filter with equalization.*

the penalty is almost 3 dB. Thus, equalization is mandatory for single-carrier scenario. Looking at the curve obtained for approximated WSS filtering and making a comparison between SD-FEC and HD-FEC, the required SNR values for SD-FEC are lower than for HD-FEC. Therefore, from a theoretical point of view, SD-FEC provides better performances than HD-FEC.

On the other hand, when actual WSS filtering is considered, HD-FEC provides better performance than SD-FEC, both with and without equalization. In fact, curves obtained using HD-FEC are less steep than those obtained using SD-FEC. Therefore, using HD-FEC the lumped noise at the receiver scenario is quite well described by theory, since the penalty from theory after 7 WSS is approximately 1 dB.

Also for the equally distributed noise scenario, equalization is necessary when actual WSS filtering is applied. As shown in Figure 3.5, without equalization, for SD-FEC the penalty is more than 2 dB after 2 WSS, while for HD-FEC 3 dB penalty occurs after 3 WSS. If equalization is considered, the penalties between the case without any WSS and the case with 7 WSS are very low (3 dB for SD-FEC and around 1 dB for HD-FEC). For this reason, also for equally distributed noise scenario, the theory is a good model for actual WSS filtering with equalization. As expected, comparing lumped noise at the receiver scenario and equally distributed noise scenario, required SNRs are lower for the second one.

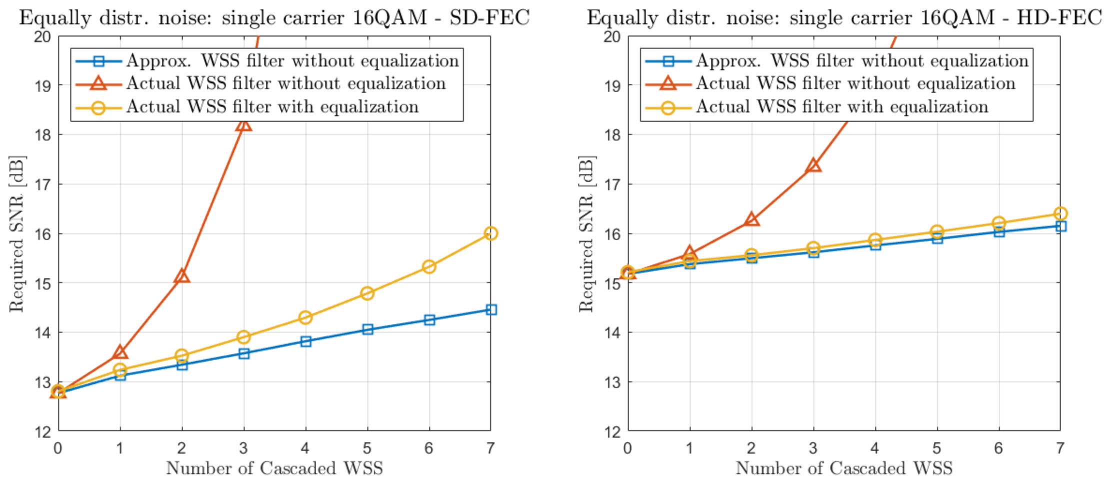


Figure 3.5: *Required SNR vs Number of Cascaded WSS for equally distributed noise in case of 32 GBaud PM-16QAM single-carrier signal and both SD-FEC and HD-FEC for approximated WSS filter without equalization, actual WSS filter without equalization and actual WSS filter with equalization.*

3.2 Multi-subcarrier modulation

In case of multi-subcarriers, different numbers of subcarriers can be considered to understand which one provides better performance and which are the advantages with respect to single-carrier approach. In this case also different power ratio strategies are studied, those presented in section 2.3: same power, minimum BER, water filling, power loading, bit loading, bit loading and water filling and bit and power loading strategies. Different number of subcarriers are studied and for each of them, first simulations with theoretical power ratios are performed for both SD-FEC and HD-FEC. Then, simulations with optimized power ratios are performed in case of bit and power loading optimization, but only for SD-FEC case, because we observed that better performance are given when SD-FEC

8x4 GBaud Modulation formats
16 16 16 16 16 16 16 16
8 16 16 32 32 16 16 8
8 8 32 32 32 32 8 8
8 8 16 64 64 16 8 8
4 16 32 32 32 32 16 4
4 16 16 64 64 16 16 4
4 8 32 64 64 32 8 4
4 4 64 64 64 64 4 4

Table 3.2: *FDHMF modulation formats using 8 subcarriers providing 200G net capacity.*

is applied, as shown below. For simulations with theoretical power ratios, the three filtering cases already considered for single-carrier are analysed: approximated WSS filtering without equalization, actual WSS filtering without equalization and actual WSS filtering with equalization. Instead, for the bit and power loading optimization, only actual WSS filtering without and with equalization are considered.

3.2.1 8 subcarriers

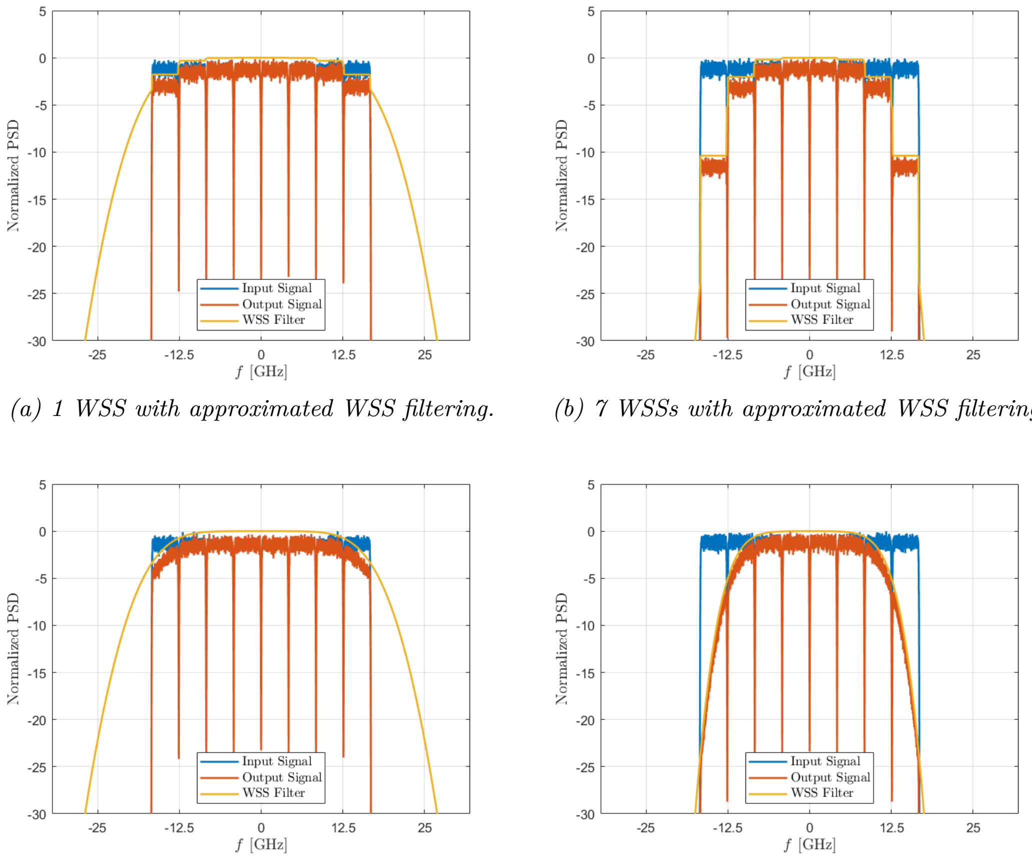
Based on results obtained in [14], to validate the theory, it is convenient to start simulation studies using 8 subcarriers, looking for performance improvements in both lumped noise at the receiver side and equally distributed noise scenarios. In this initial study, all the power ratio strategies presented in section 2.3 are applied. The FDHMF subcarrier modulation formats which provide 200G net capacity are reported in Table 3.2. In general, different power ratio strategies performances are analysed by just using 8x16QAM as modulation format for each subcarrier regardless the number of cascaded WSS, except in case of bit loading, bit loading and water filling, and bit and power loading. In fact, since they search for the best constellation, all the constellations of Table 3.2 are considered.

Lumped noise at the receiver

In this type of simulation, modulation formats are automatically provided by the simulated MATLAB code. The analysed input modulation format per subcarrier is always 8x16QAM, independently from the number of cascaded WSS. In case of bit loading, a better modulation format can be provided among those of Table 3.2.

SD-FEC In Figure 3.6, it is possible to see the filtering effects due to the increasing number of ROADMs when the two different types of filtering (approximated WSS filtering and actual WSS filtering) and SD-FEC is considered. If HD-FEC is used, the shape of the transfer function does not change; only its bandwidth occupation changes, moving from 32 GHz to 28 GHz.

An important parameter to be evaluated is the required SNR per each number of cascaded WSS needed to get the target BER ($2 \cdot 10^{-2}$ for SD-FEC and $3.8 \cdot 10^{-3}$ for HD-FEC). Results of required SNR versus the number of cascaded WSS for lumped noise at the receiver scenario are shown in Figures 3.7 and 3.8. Analysing the scenario in which SD-FEC



(a) *1 WSS with approximated WSS filtering.*

(b) *7 WSSs with approximated WSS filtering.*

(c) *1 WSS with actual/real WSS filtering.*

(d) *7 WSSs with actual/real WSS filtering.*

Figure 3.6: *Examples of ROADM transfer function and its effect on the spectrum of an 8x4 GBaud input signal with two different filtering (approximated WSS filtering and actual WSS filtering) and SD-FEC.*

is used (Figure 3.7), it results that the strategy giving the worst performance is water filling. In this case, curves are obtained only using 8x16QAM as modulation format for each number of cascaded WSS; the other hybrid modulation formats are not analysed. For approximated WSS filtering without equalization, which is the theoretical behaviour, there is a penalty of more than 12 dB between the required SNR for 0 WSS and the required SNR for 6 WSS, which increases passing through 7 cascaded WSS. This penalty is even larger for actual WSS filtering without and with equalization and this is not acceptable. Other not effective strategies, but not so much as water filling, are same power and minimum BER strategies, which always use 8x16QAM modulation format per each subcarrier as well. If equalization is not applied, in case of approximated WSS filtering, the penalties between the required SNR of 0 WSS and the required SNR of 7 WSS are around 7 dB, but looking at the case with actual WSS filtering without equalization, the penalties become huge already after 4 WSS.

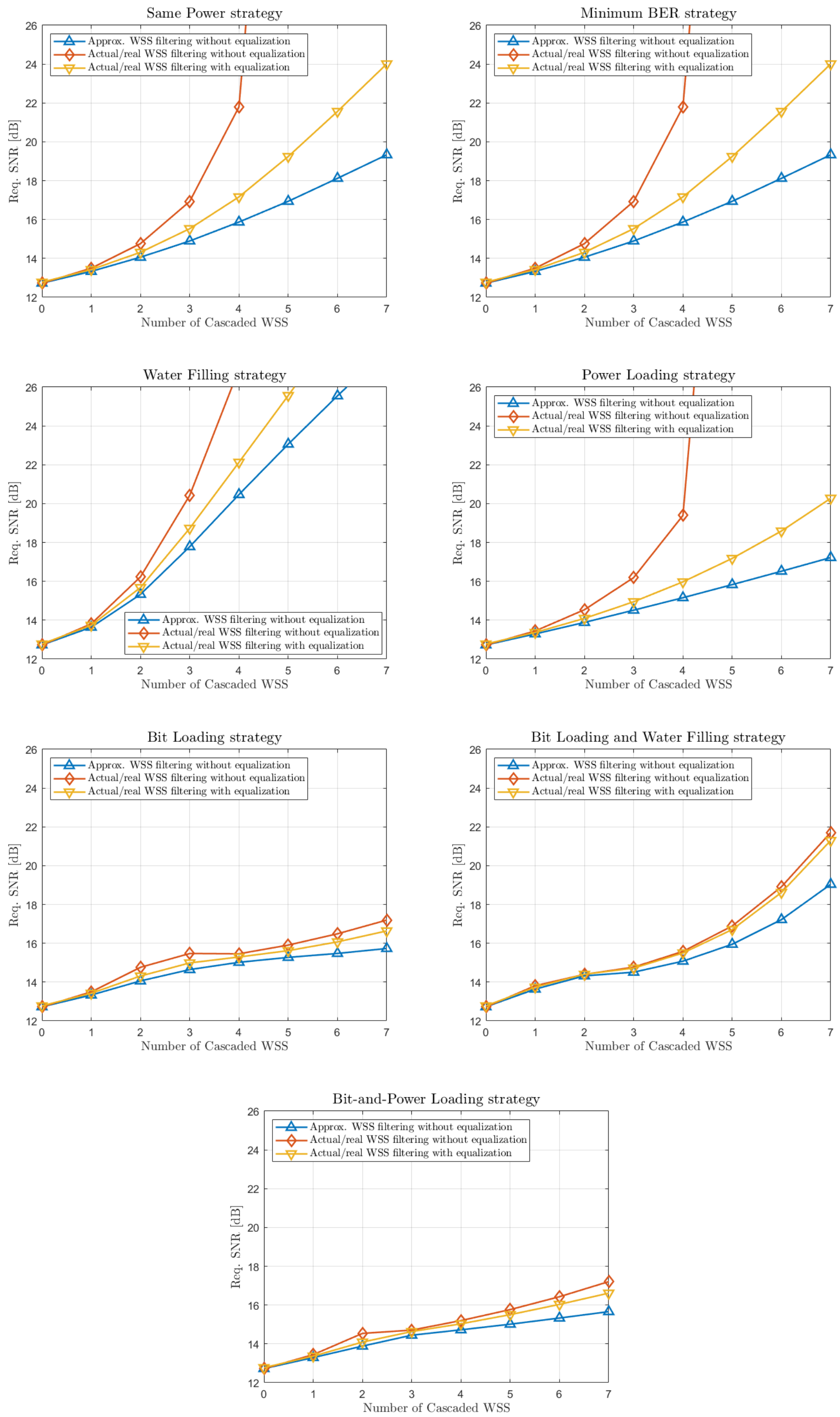


Figure 3.7: *Required SNR vs Number of Cascaded WSS for lumped noise at the receiver in case of 8x4 GBaud SCM signal and SD-FEC when different power ratios strategies are applied.*

N_{WSS}	Modulation Format per SC		
	Bit Loading strategy	*Bit Loading and Water Filling strategy*	*Bit and Power Loading strategy*
0	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
2	16 16 16 16 16 16 16 16	4 16 32 32 32 32 16 4	16 16 16 16 16 16 16 16
3	8 16 16 32 32 16 16 8	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
5	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
6	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
7	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4

Table 3.3: *Best FDHMF modulation formats based on theoretical power ratios for 8x4 GBaud SCM signal when Bit Loading, Bit Loading and Water Filling and Bit and Power Loading strategies are used with SD-FEC technique in lumped noise at the receiver scenario. Each column is referred to approximated WSS filtering, actual WSS filtering without equalization and actual WSS filtering with equalization.*

This consideration can be made also for power loading strategy. Penalties decrease when equalization is applied; in fact, although penalties are still high for same power, minimum BER and water filling strategies, some improvements are obtained when power loading strategy is used. In this case penalty is about 7 dB, which unfortunately is still not acceptable. Better performance is obtained when bit loading is applied. In fact, for each number of cascaded WSS, it finds the modulation format which provides the lowest required SNR. As a consequence, the penalty in case of actual WSS filtering without equalization, which is the worst among the three, is a little bit higher than 4 dB. Instead, for the approximated WSS filtering, the penalty is 3 dB. After having analysed performace of all the FDHMF constellations, the best modulation formats per number of WSS in case of bit loading, bit loading and water filling and bit and power loading strategies are reported in Table 3.3.

Depending on the applied power ratio strategy, the best modulation format for a fixed number of WSS could be different. In fact, as instance, when there are 3 cascaded WSS, the simulation of bit loading strategy, based on approximated WSS filtering, finds that the best configuration is the hybrid [8 16 16 32 32 16 16 8] modulation; instead bit loading and water filling and bit and power loading strategies find that the best one is the [4 16 32 32 32 32 16 4]. The best modulation formats are obtained on the basis of the theoretical power ratios and approximated WSS filtering, therefore, all the decisions are taken based on the required SNR experienced by the theoretical behaviour of the system. For this reason, the best modulation formats could not be optimal when actual/real WSS filtering and equalization are applied. To make better decisions, an optimization based on optimized power ratios is necessary. First, power loading strategy is used for each 8 multi subcarrier modulation format providing 200G net capacity, then, among them, bit loading is performed to determine the constellations requiring the minimum SNR for each number of cascaded WSS.

N_{WSS}	Modulation Format per SC		
	Approx. WSS filtering No equalization	*Actual WSS filtering No equalization*	*Actual WSS filtering Equalization*
0	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
2	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
3	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
4	16 16 16 16 16 16 16 16	8 16 16 32 32 16 16 8	16 16 16 16 16 16 16 16
5	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8
6	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8
7	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8

Table 3.4: *Best FDHMF modulation formats per subcarrier based on theoretical power ratios for 8x4 GBaud SCM signal using Bit Loading strategy with all the three types of WSS filtering and HD-FEC technique in lumped noise at the receiver scenario.*

N_{WSS}	Modulation Format per SC		
	Approx. WSS filtering No equalization	*Actual WSS filtering No equalization*	*Actual WSS filtering Equalization*
0	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
2	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8
3	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8
4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
5	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
6	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
7	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4

Table 3.5: *Best FDHMF modulation formats per subcarrier based on theoretical power ratios for 8x4 GBaud SCM signal using Bit Loading and Water Filling strategy with all the three types of WSS filtering and HD-FEC technique in lumped noise at the receiver scenario.*

HD-FEC When HD-FEC is used (Figure 3.8), similar considerations, as for SD-FEC, can be made about the required SNR per number of cascaded WSS.

In fact, when same power, minimum BER, water filling and power loading strategies are used and the signal is filtered by the actual WSS filter, equalization is mandatory to reduce the penalties to acceptable levels. Bit loading, bit loading and water filling and bit and power loading strategies provide good performance also when equalization is not used since penalties between the required SNR for 0 WSS and the required SNR for 7 WSS are about 2 dB. Unlike SD-FEC, in case of HD-FEC the best modulation formats obtained from simulations may be different when different types of filter are used (approximated WSS filtering without equalization and actual WSS filtering without and with equalization). They are reported in Tables 3.4, 3.5 and 3.6 and they refer respectively to bit loading, bit loading and water filling, and bit and power loading strategies.

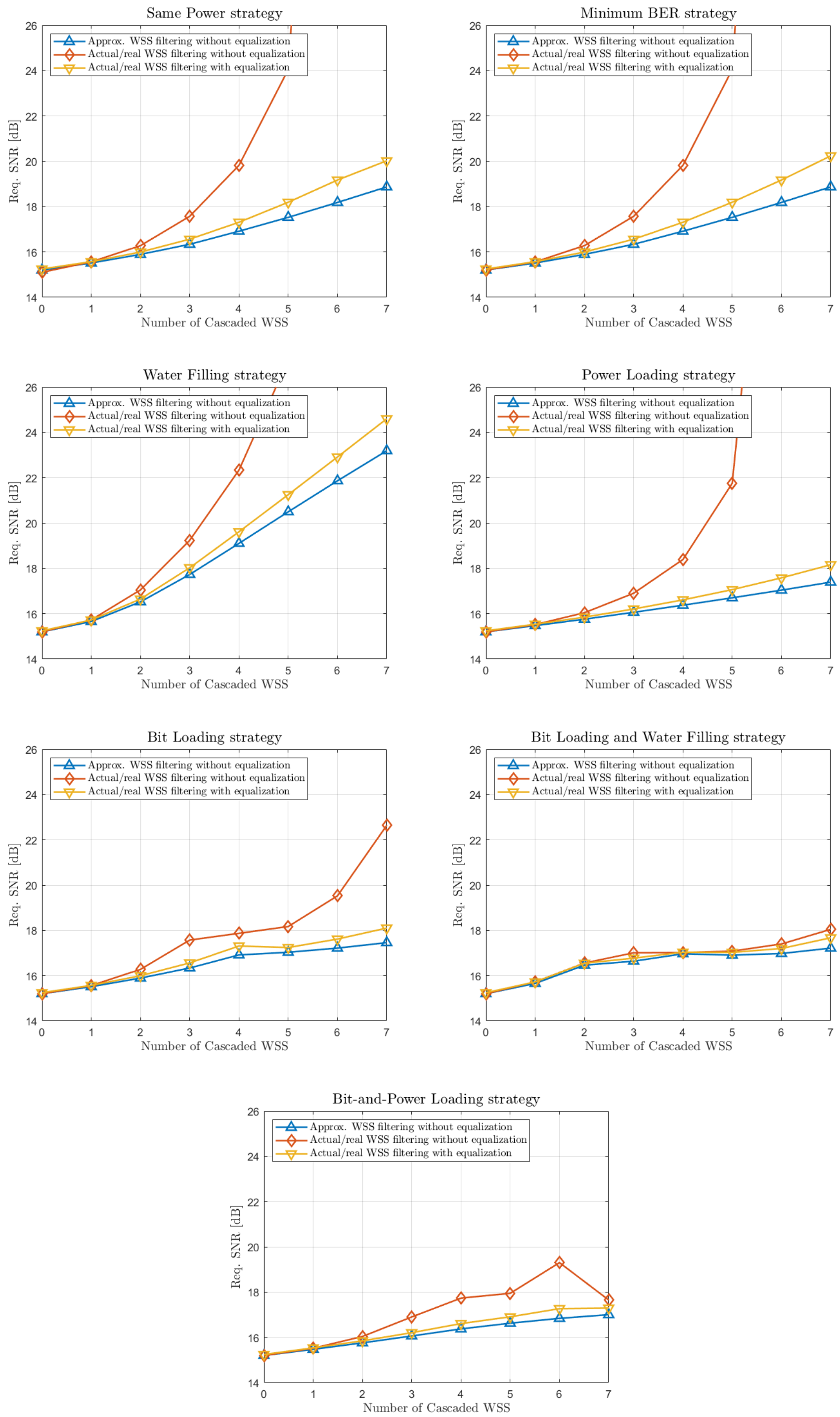


Figure 3.8: *Required SNR vs Number of Cascaded WSS for lumped noise at the receiver in case of 8x4 GBaud SCM signal and HD-FEC when different power ratios strategies are applied.*

N_{WSS}	Modulation Format per SC		
	Approx. WSS filtering No equalization	*Actual WSS filtering No equalization*	*Actual WSS filtering Equalization*
0	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
2	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
3	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
4	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
5	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8
6	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8
7	8 16 16 32 32 16 16 8	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4

Table 3.6: *Best FDHMF modulation formats per subcarrier based on theoretical power ratios for 8x4 GBaud SCM signal using Bit and Power Loading strategy with all the three types of WSS filtering and HD-FEC technique in lumped noise at the receiver scenario.*

Also for HD-FEC, when bit loading is performed, the best modulation format is determined based on the theoretical behaviour (lumped noise at the receiver and approximated WSS filter), thus the selected modulation formats may not be the best when actual filtering and equalization are simulated. This effect can be observed in case of bit and power loading strategy. In fact, when actual WSS filtering without equalization is used, the SNR required when there are 5 and 6 cascaded WSS is higher than when 7 WSS are crossed. This can be explained by looking at Table 3.6, column in the center. There it can be seen that, moving from 6 to 7 WSS, the best modulation formats, found based on theoretical power ratios, are different. In particular, when there are 6 WSS, the best constellation is [8 16 16 32 32 16 16 8], whereas when there are 7 WSS, the best one is [4 16 32 32 32 32 16 4].

Since the required SNR is higher for 5 and 6 WSS than for 7 cascaded WSS, it may exist a modulation format that provides better performance than [8 16 16 32 32 16 16 8], which could be the one used for 7 WSS. This suggests that the choice made by the theory could not be the best one. Actually, to find the best modulation format, it is necessary to perform the same optimization process previously proposed for SD-FEC technique.

SD-FEC vs HD-FEC SD-FEC occupies more bandwith than HD-FEC, since the symbol rate of the multi-subcarrier signal is 32 GBaud, therefore is more affected by WSS filtering. At the same time it has a lower BER, i.e. a better FEC. How are these two characteristics combined together? Let us see.

SD-FEC and HD-FEC provide different performance depending on the number of cascaded WSS; at this point it is useful to understand which is the best one for a given number of WSS. Figures 3.9 and 3.10 show a comparison between the performance obtained when SD-FEC is applied and those obtained when HD-FEC is used for different power ratio strategies respectively for actual WSS filtering without equalization and actual WSS filtering with equalization.

In general, the simulation curves obtained with actual WSS filtering and with the approximated WSS filtering for HD-FEC are closer to each other than those obtained for SD-FEC, resulting in lower penalties.

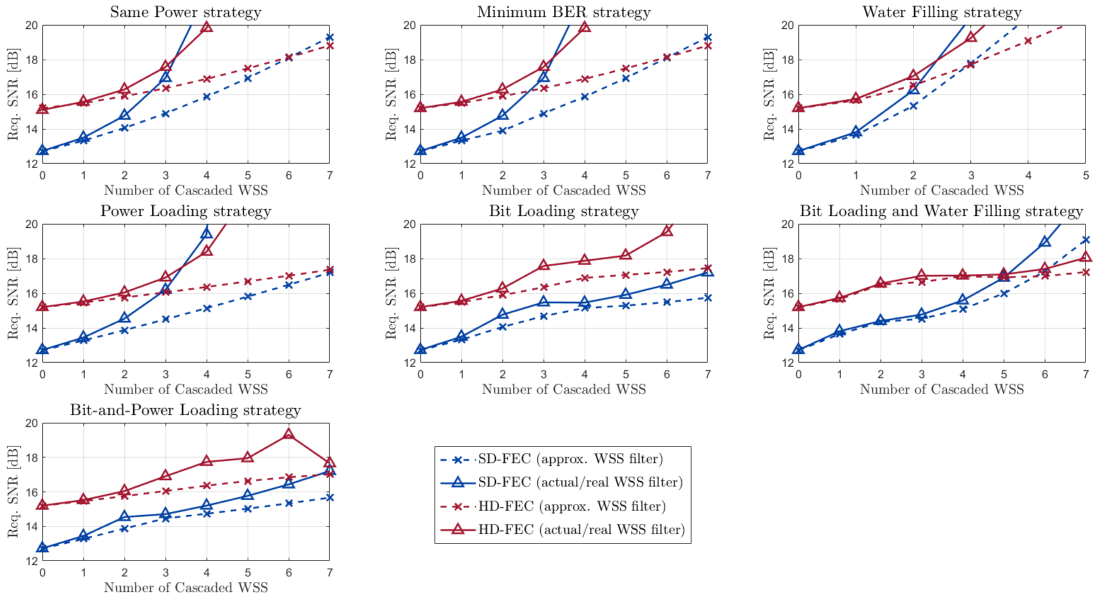


Figure 3.9: *Comparison between SD-FEC and HD-FEC in terms of Required SNR vs Number of Cascaded WSS for 8x4 GBaud SCM signal and lumped noise at the receiver when different power ratio strategies are applied. Actual WSS filtering is without equalization.*

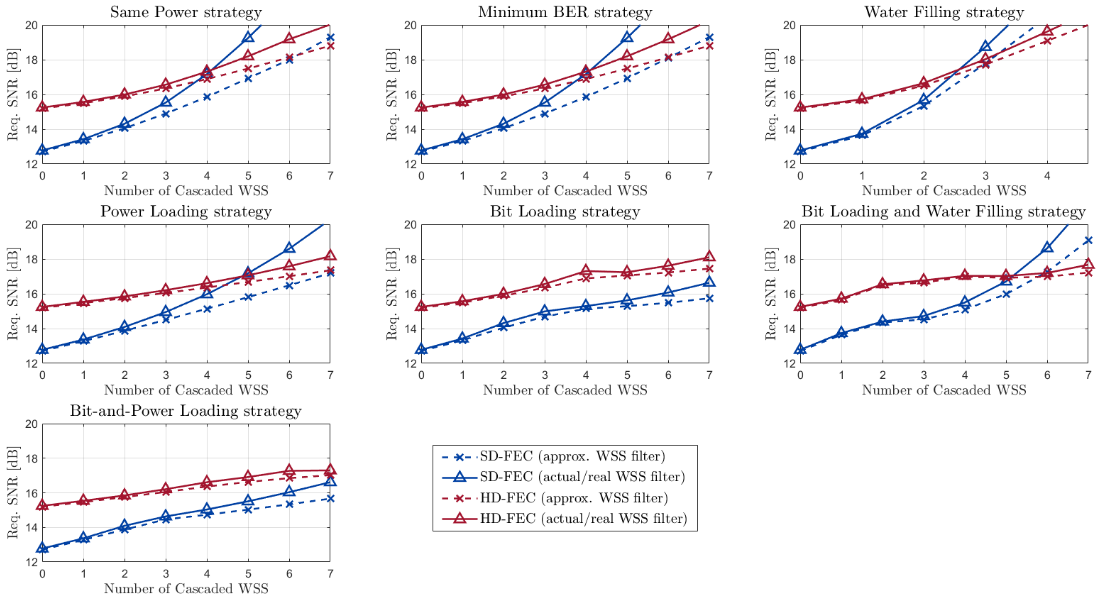


Figure 3.10: *Comparison between SD-FEC and HD-FEC in terms of Required SNR vs Number of Cascaded WSS for 8x4 GBaud SCM signal and lumped noise at the receiver when different power ratio strategies are applied. Actual WSS filtering is with equalization.*

As already observed, if bit loading is not performed, simulation performance starts to worsen after few WSS both without and with equalization. SD-FEC is better when there are few WSS, whereas when there are more than 4 WSS for same power, minimum BER and power loading strategies, and more than 2 WSS for water filling strategy, the curve starts to grow faster than for HD-FEC, which thus provides better performance as it requires a lower SNR. HD-FEC provides better results than SD-FEC also for bit loading and water filling strategy, but in this case after a higher number of WSS (5 or 6 depending on the type of filtering, approximated WSS filtering or actual WSS filtering). For bit loading and bit and power loading strategies, the general trend is that, up to 7 cascaded WSS, SD-FEC requires lower SNR to get the target BER with respect to HD-FEC, for both approximated WSS filtering and actual WSS filtering.

These results show that the best performance is obtained when bit loading and bit and power loading strategies are used in combination with SD-FEC technique, both without and with equalization. In fact, also without equalization with 7 WSS, the penalties between the curve obtained with approximated WSS filtering and those obtained with actual WSS filtering are less than 3 dB. This leads to say that using the actual/real WSS filter, system behaves very similarly to the theory. Giving more attention to bit and power loading, the SNR penalty between 0 WSS and 7 WSS is about 5 dB, when no equalization is used, and almost 4 dB in case of equalization. Therefore, the use of equalization is needed when there are more than 5 WSS, since, without equalization, the penalty is already about 3 dB.

Lumped noise at the receiver: bit and power loading optimization based on optimized power ratios

According to previous results, best performance is experienced when SD-FEC technique is used in combination with bit and power loading strategy. Now it is fundamental to check if the modulation formats found by quick-evaluation simulations based on theoretical power ratios are actually the best also for simulations based on optimized power ratios.

This corresponds to the optimization of bit and power loading strategy. First, it performs power loading applying iteratively *fminsearch* function to find the optimal power ratios delivering the lowest SNR per subcarrier. Then, it performs bit loading to find the best modulation format among all possible 8 MSC ones providing a total capacity of 200G.

The three modulation formats requiring the lowest SNR are: 8x16QAM, [8 16 16 32 32 16 16 8] and [4 16 32 32 32 32 16 4]. Over these three it is possible to choose the best one for each number of cascaded WSS, both without and with equalization (Table 3.7).

In Figure 3.11 the red dashed lines represent bit and power loading performed on theoretical power ratios basis. In particular, they are respectively the orange and the yellow lines reported in Figure 3.8 in picture on the right. Without equalization, simulations without power ratio optimization and simulations with power ratio optimization result in the same choice in terms of best modulation formats, except when the cascaded WSS are 2. In fact, based on theory, 8x16QAM is still the best one, instead based on simulation optimization, [4 16 16 32 32 16 16 4] is the best. With equalization and with 0 cascaded WSS, the best constellation is [8 16 16 32 32 16 16 8], but 8x16QAM is expected to be the best, even though their penalty is very small. This occurs because of machine precision and simulation uncertainty. In fact, power ratios are derived from a SNR obtained from

N_{WSS}	Modulation Format per SC	
	Actual WSS filtering *No equalization*	*Actual WSS filtering* *Equalization*
0	16 16 16 16 16 16 16 16	8 16 16 32 32 16 16 8
1	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
2	4 16 32 32 32 32 16 4	16 16 16 16 16 16 16 16
3	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
4	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
5	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
6	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4
7	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4

Table 3.7: Best modulation formats per subcarrier based on optimized power ratios for 8x4 GBaud SCM signal using Bit and Power Loading strategy with all the three types of WSS filtering and SD-FEC technique in lumped noise at the receiver scenario.

simulation, hence affected by uncertainty as well. Also power ratios obtained with simulation optimization are not so different from the theoretical ones, as reported in Tables 3.8 and 3.9 in case of no equalization, and Tables 3.10 and 3.11 in case of equalization.

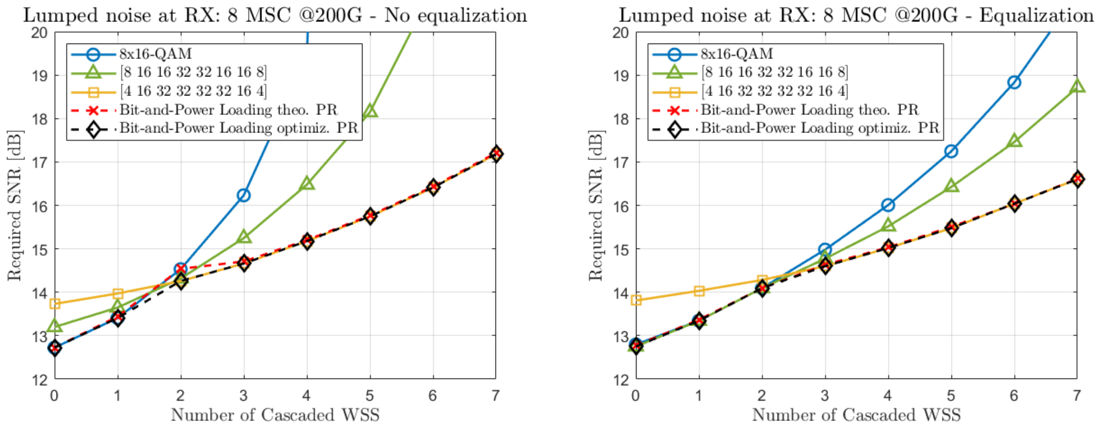


Figure 3.11: *Best constellations, Bit and Power Loading based on theoretical PRs (red dashed line) and Bit and Power Loading based on optimized PRs (black dashed line) without equalization (on the left) and with equalization (on the right) for an 8x4GBaud SCM signal and noise lumped at the receiver.*

Equally distributed noise

In a more realistic scenario, noise is equally distributed along the link, so it would be useful to understand how much the lumped noise scenario is worse than this one. In fact, when the noise is lumped at the receiver, only the transmitted signal is filtered, not the noise, therefore the effect of noise is not attenuated, but stronger.

Based on results obtained for the lumped noise at receiver side scenario, the analysis of the equally distributed noise is performed only applying SD-FEC technique and power

N_{WSS}	Power ratio per subcarrier [dB]							
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.7	-0.1	-0.3	-0.3	-0.3	-0.3	-0.1	0.7
2	1.4	-0.3	-0.7	-0.7	-0.7	-0.7	-0.3	1.4
3	-3.0	-0.5	1.2	1.1	1.1	1.2	-0.5	-3.0
4	-2.3	-0.5	1.0	1.0	1.0	1.0	-0.5	-2.3
5	-1.6	-0.5	0.9	0.8	0.8	0.9	-0.5	-1.6
6	-0.9	-0.6	0.7	0.6	0.6	0.7	-0.6	-0.9
7	-0.3	-0.6	0.5	0.3	0.3	0.5	-0.6	-0.3

Table 3.8: Theoretical power ratios obtained for Bit and Power Loading applied to an 8x4 GBaud MSC signal without equalization in lumped noise at the receiver scenario.

N_{WSS}	Power ratio per subcarrier [dB]							
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.8	0.0	-0.1	-0.4	-0.4	-0.1	0.0	0.8
2	-3.6	-0.3	1.4	1.4	1.4	1.4	-0.3	-3.6
3	-2.4	-0.4	1.1	1.3	1.3	1.1	-0.4	-2.4
4	-1.9	-0.3	1.1	0.9	0.9	1.1	-0.3	-1.9
5	-1.2	-0.2	0.7	0.8	0.8	0.7	-0.2	-1.2
6	-0.8	-0.5	0.5	0.5	0.5	0.5	-0.5	-0.8
7	0.1	-0.2	0.1	0.1	0.1	0.1	-0.2	0.1

Table 3.9: Optimized power ratios obtained for Bit and Power Loading applied to an 8x4 GBaud MSC signal without equalization in lumped noise at the receiver scenario.

ratio strategies involving bit and/or power loading; the theory is still the one of the noise lumped at the receiver. In Figure 3.12 the resulting required SNR versus the number of cascaded WSS are reported. When power loading strategy is used, the penalty after 3 WSS is almost 3 dB, thus it is better to perform some equalization. As expected, also when the noise is equally distributed, the best performance, i.e. lower penalties, is given by bit loading and bit and power loading strategies, for which penalties are about 3 dB after 7 WSS.

Another interesting result is that penalties between curves of actual WSS filtering with equalization and approximated WSS filtering without equalization (theory) after 7 WSS are negligible, so theory analysis is enough to understand the behaviour of an equally distributed noise scenario when equalization is applied.

When performing bit loading, the resulting best modulation formats are the same as those found for lumped noise at the receiver scenario. Since the simulation is based on the theoretical power ratios obtained when the noise is lumped at the receiver, these configurations could not be the optimal ones. To find them, the optimization of bit and power loading based on simulations is necessary, as follows.

N_{WSS}	Power ratio per subcarrier [dB]							
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.7	-0.1	-0.3	-0.3	-0.3	-0.3	-0.1	0.7
2	1.3	-0.3	-0.6	-0.7	-0.7	-0.6	-0.3	1.3
3	-3.0	-0.5	1.2	1.1	1.1	1.2	-0.5	-3.0
4	-2.3	-0.5	1.0	1.0	1.0	1.0	-0.5	-2.3
5	-1.6	-0.5	0.9	0.8	0.8	0.9	-0.5	-1.6
6	-1.0	-0.6	0.7	0.6	0.6	0.7	-0.6	-1.0
7	-0.4	-0.6	0.5	0.4	0.4	0.5	-0.6	-0.4

Table 3.10: Theoretical power ratios obtained for Bit and Power Loading applied to an 8x4 GBaud MSC signal with equalization in lumped noise at the receiver scenario.

N_{WSS}	Power ratio per subcarrier [dB]							
0	-2.0	-0.4	-0.4	1.7	1.7	-0.4	-0.4	-2.0
1	0.6	0.0	-0.3	-0.4	-0.4	-0.3	0.0	0.6
2	1.4	-0.5	-0.7	-1.1	-1.1	-0.7	-0.5	1.4
3	-2.4	-0.4	1.1	1.3	1.3	1.1	-0.4	-2.4
4	-1.9	-0.3	1.1	0.9	0.9	1.1	-0.3	-1.9
5	-1.1	-0.2	0.7	0.8	0.8	0.7	-0.2	-1.1
6	-0.8	-0.5	0.5	0.5	0.5	0.5	-0.5	-0.8
7	0.1	-0.2	0.1	0.1	0.1	0.1	-0.2	0.1

Table 3.11: Optimized power ratios obtained for Bit and Power Loading applied to an 8x4 GBaud MSC signal with equalization in lumped noise at the receiver scenario.

Equally distributed noise: bit and power loading optimization based on optimized power ratios

As for lumped noise case, the optimization is performed studying all the modulation formats multiplexed over 8 subcarriers which provide 200G and, among them, only those requiring lower SNR are selected. For equally distributed noise scenario, like for lumped noise at the receiver scenario, the best are 8x16QAM, [8 16 16 32 32 16 16 8] and [4 16 32 32 32 32 16 4], as shown in Figure 3.13. There, for both cases, a significant result is shown since bit loading based on theoretical power ratios agrees with bit loading based on optimized power ratios even though the theory is obtained for lumped noise at the receiver. This means that, for an 8x4 GBaud SCM signal, the theory for lumped noise at the receiver is a good model also for the equally distributed noise scenario.

As for the case of noise lumped at the receiver, it is possible to make a comparison between theoretical power ratios and optimized power ratios used in bit and power loading optimization, which are reported in Tables 3.12-3.15.

Lumped noise at the receiver vs equally distributed noise

At this point it is useful to understand which is the gain when the noise is equally distributed against when the noise is lumped at the receiver in terms of required SNR varying the number of cascaded WSS. Previous results show that, to obtain very low penalties, equalization is mandatory; therefore, to see the advantages of equally distributed noise

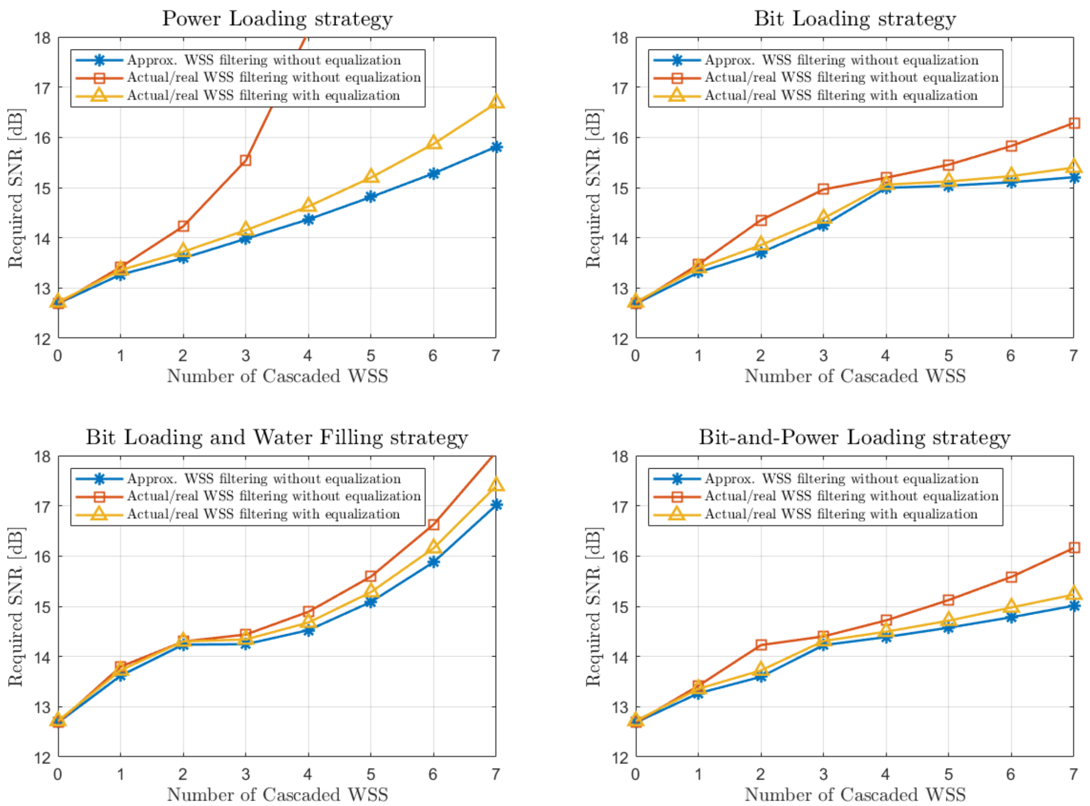


Figure 3.12: *Required SNR vs Number of Cascaded WSS for equally distributed noise in case of 8x4 GBaud SCM signal and SD-FEC when Power Loading, Bit Loading, Bit Loading and Water Filling, and Bit and Power loading strategies are applied.*

N_{WSS}	Power ratio per subcarrier [dB]							
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.4	-0.1	-0.1	-0.2	-0.2	-0.1	-0.1	0.4
2	0.7	-0.1	-0.3	-0.4	-0.4	-0.3	-0.1	0.7
3	1.1	-0.2	-0.5	-0.5	-0.5	-0.5	-0.2	1.1
4	1.4	-0.3	-0.7	-0.7	-0.7	-0.7	-0.3	1.4
5	-0.1	-0.5	-1.0	1.3	1.3	-1.0	-0.5	-0.1
6	0.2	-0.6	-1.1	1.2	1.2	-1.1	-0.6	0.2
7	-2.8	-0.6	1.2	1.1	1.1	1.2	-0.6	-2.8

Table 3.12: Theoretical power ratios obtained for Bit and Power Loading applied to an 8x4 GBaud MSC signal without equalization in an equally distributed noise scenario.

over lumped noise at the receiver, in Figure 3.14, their comparison is performed considering actual WSS filtering with equalization in combination with different power ratio strategies.

As expected, increasing the number of cascaded WSS, performance in case of equally distributed noise is better than in case of lumped noise at the receiver, since the required SNR is lower. In fact, althought there is no difference between the two scenarios when

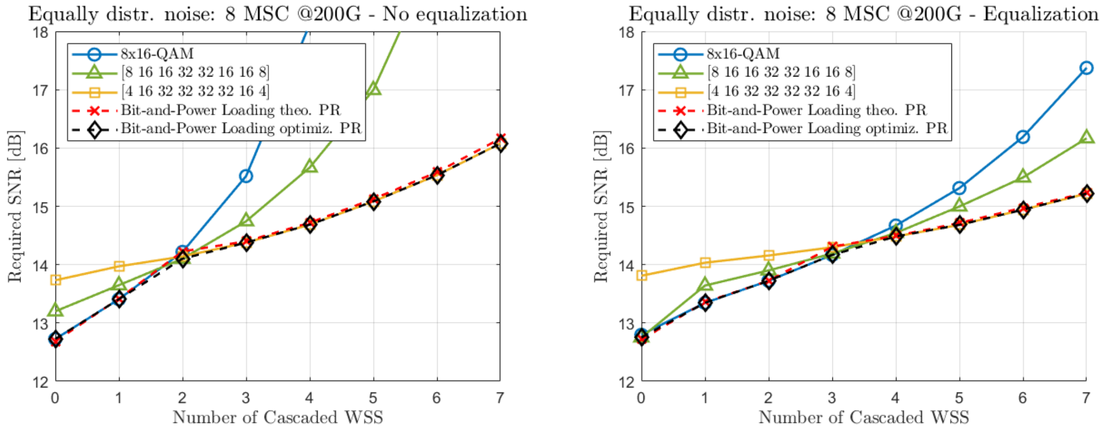


Figure 3.13: *Best constellations, Bit and Power Loading based on theoretical PRs (red dashed line) and Bit and Power Loading based on optimized PRs (black dashed line) without equalization (on the left) and with equalization (on the right) for an 8x4GBaud SCM signal and equally distributed noise.*

N_{WSS}	**Power ratio per subcarrier [dB]**							
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.8	0.0	-0.1	-0.4	-0.4	-0.1	0.0	0.8
2	-3.6	-0.3	1.4	1.4	1.4	1.4	-0.3	-3.6
3	-2.4	-0.4	1.1	1.3	1.3	1.1	-0.4	-2.4
4	-1.9	-0.3	1.1	0.9	0.9	1.1	-0.3	-1.9
5	-1.2	-0.2	0.7	0.8	0.8	0.7	-0.2	-1.2
6	-0.8	-0.5	0.5	0.5	0.5	0.5	-0.5	-0.8
7	0.1	-0.2	0.1	0.1	0.1	0.1	-0.2	0.1

Table 3.13: Optimized power ratios for Bit and Power Loading applied to an 8x4 GBaud MSC signal without equalization in an equally distributed noise scenario.

there is just 1 cascaded WSS, when there are more WSS, there is a gain for the equally distributed noise scenario with respect to the lumped noise at the receiver scenario. With 7 cascaded WSS, in case of power loading and bit loading and water filling strategies, the gain of equally distributed noise scenario over lumped noise at receiver scenario is higher than 3 dB. Whereas, when bit loading and bit and power loading strategies are applied, the gain is around 2 dB.

3.2.2 Single-carrier versus 8 subcarriers

To understand which are the advantages of using 8 subcarriers instead of using single-carrier, the following figures show some comparisons in terms of required SNR between single-carrier and 8 subcarrier modulation formats when SD-FEC technique is applied. Both types of noise insertion are analysed.

Considering noise lumped at the receiver, curves on the left picture of Figure 3.15 are obtained when the approximated WSS filter is used and no equalization is performed. In

N_{WSS}	Power ratio per subcarrier [dB]							
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.4	0.0	-1.5	-0.2	-0.2	-1.5	0.0	0.4
2	0.7	-0.1	-0.3	-0.3	-0.3	-0.3	-0.1	0.7
3	1.0	-0.2	-0.5	-0.5	-0.5	-0.5	-0.2	1.0
4	1.3	-0.3	-0.7	-0.7	-0.7	-0.7	-0.3	1.3
5	-0.1	-0.5	-0.9	1.3	1.3	-0.9	-0.5	-0.1
6	0.2	-0.6	-1.1	1.1	1.1	-1.1	-0.6	0.2
7	-2.8	-0.5	1.1	1.1	1.1	1.1	-0.5	-2.8

Table 3.14: Theoretical power ratios obtained for Bit and Power Loading applied to an 8x4 GBaud MSC signal with equalization in an equally distributed noise scenario.

N_{WSS}	Power ratio per subcarrier [dB]							
0	-2.0	-0.4	-0.4	1.7	1.7	-0.4	-0.4	-2.0
1	0.6	0.0	-0.3	-0.4	-0.4	-0.3	0.0	0.6
2	1.0	-0.6	-0.5	-0.7	-0.7	-0.5	-0.6	1.0
3	-3.0	0.0	1.1	1.1	1.1	1.1	0.0	-3.0
4	-2.8	0.0	1.1	1.1	1.1	1.1	0.0	-2.8
5	-2.4	-0.2	1.1	1.2	1.2	1.1	-0.2	-2.4
6	-2.0	-0.3	0.9	0.9	0.9	0.9	-0.3	-2.0
7	-1.6	0.0	0.8	0.7	0.7	0.8	0.0	-1.6

Table 3.15: Optimized power ratios for Bit and Power Loading applied to an 8x4 GBaud MSC signal with equalization in an equally distributed noise scenario.

this case, single-carrier provides good performance since the penalty between having 0 WSS and having 7 WSS is less than 2 dB, and the curve seems to have a logarithmic behaviour. Instead, with 8 subcarriers performance gets worse, in particular when the power of each subcarrier is flat (flat power strategy). Results improve a little bit when bit loading and bit and power loading are applied, since their curves tend to be logarithmic and the penalty between 0 and 7 WSS is less than 3 dB.

The advantage of using 8 subcarriers against single-carrier is visible in the picture on the right of Figure 3.15, when the filtering is performed with the actual WSS filter, for which equalization is mandatory, as already discussed before. Now the curve for single-carrier scenario tends to an exponential behaviour with a penalty of 6 dB between the SNR required at 0 WSS and the one required at 7 WSS. The curve associated to 8 subcarriers with flat power is still worse than the single-carrier one. On the other hand, curves obtained applying bit loading and bit and power loading start to require lower SNRs when more than 3 WSS are present. Passing through 7 cascaded WSS, the maximum gain of subcarrier multiplexing over single-carrier is larger than 2 dB.

Analysing the scenario with equally distributed noise (Figure 3.16), in case of approximated WSS filtering and no equalization, even though penalties for 8 subcarriers are lower than when the noise is lumped at the receiver, performance of single-carrier is still better. Instead, in case of actual WSS filtering and equalization, the advantage of using 8 subcarriers against single-carrier is no longer present. Among the three curves related to 8 subcarriers, the curve closer to the single-carrier one is the 8 subcarriers with bit and power

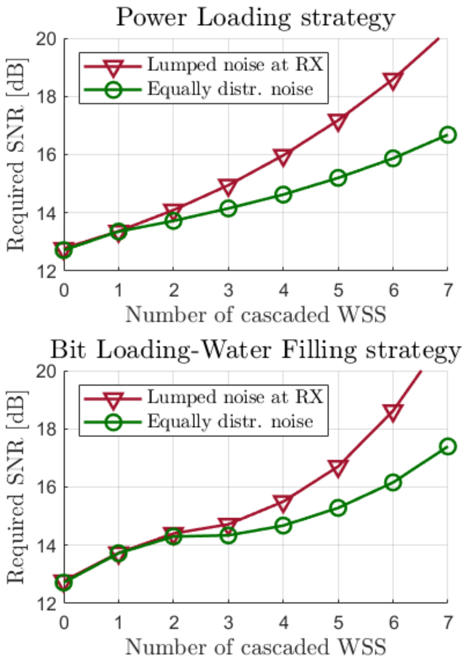


__Figure 3.14:__ Comparison between lumped noise at RX and equally distributed noise scenarios for a 8x4 GBaud MSC signal and SD-FEC when Flat Power, Bit Loading and Bit and Power Loading strategies are applied in case of actual WSS filtering with equalization.

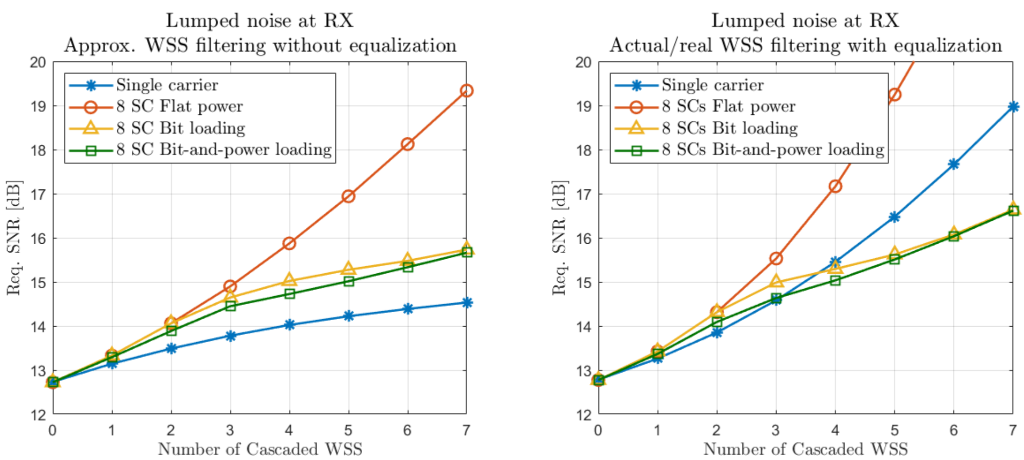


__Figure 3.15:__ Comparison between single-carrier and 8 subcarriers scenarios in case of lumped noise at the receiver. The 8x4 GBaud MSC signal is subjected to different power ratio strategies: Flat Power, Bit Loading and Bit and Power Loading.

loading, which almost overlap the curve of single-carrier. In fact, penalties are negligible, but performance of single-carrier is still better.

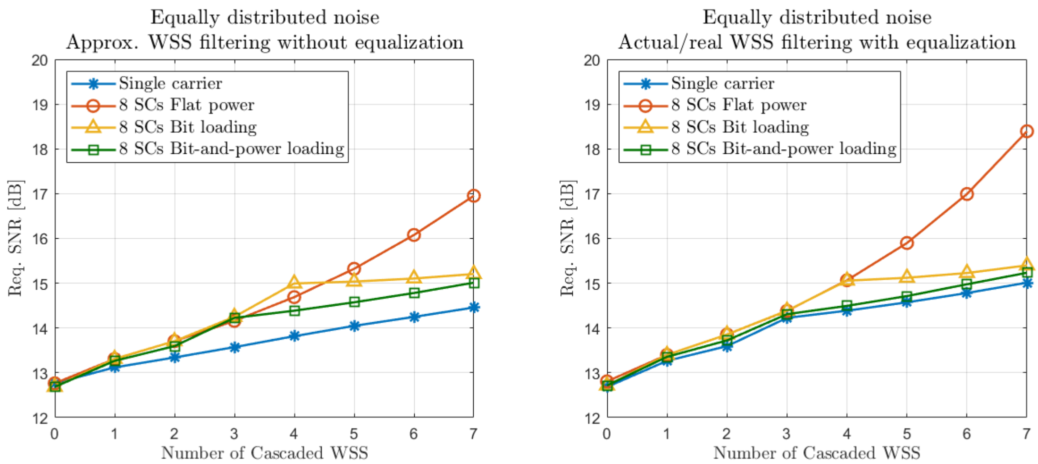


Figure 3.16: *Comparison between single-carrier and 8 subcarriers scenarios in case of equally distributed noise. The 8x4 GBaud MSC signal is subjected to different power ratio strategies: Flat Power, Bit Loading and Bit and Power Loading.*

4x8 GBaud Modulation formats
16 16 16 16
8 32 32 8
4 64 64 4

Table 3.16: Modulation formats using 4 subcarriers providing 200G net capacity.

3.2.3 4 subcarriers

Now it is interesting to understand whether it could be convenient somehow to halve the number of subcarriers, since it would reduce system complexity, as the number of subcarriers is smaller. Since performance is expected to be worse than using 8 subcarriers, only power ratio strategies providing better performance for 8 subcarriers are analysed here. First, for both types of noise insertion (lumped noise at the receiver and equally distributed noise), time-domain simulation based on theoretical power ratios is performed, then simulation with optimized power ratios follows. Configurations using 4 subcarriers which provide 200G of net capacity are reported in Table 3.16.

Lumped noise at the receiver

As in the analysis for 8 subcarriers, both SD-FEC and HD-FEC techniques are considered; system performance trends are depicted respectively in Figures 3.17 and 3.18.

SD-FEC In case of SD-FEC (Figure 3.17) and approximated WSS filtering (blue curve), the penalties between 0 WSS and 7 WSS is around 3 dB for all the considered power ratio strategies. This is due to the fact that system behaviour is closer to a single-carrier system, for which the penalty is almost 2 dB. When the actual WSS filter is used, which is no longer the ideal behaviour, penalties become very big, denoting that filtering effects are

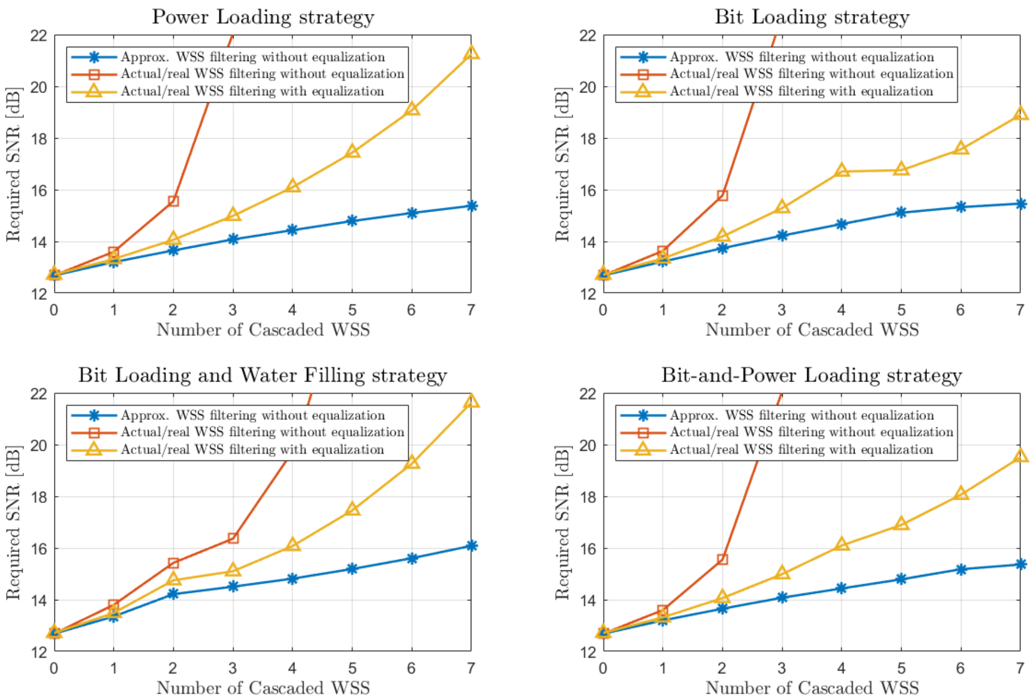


Figure 3.17: *Required SNR vs Number of Cascaded WSS for lumped noise at the receiver in case of 4x8 GBaud SCM signal and SD-FEC when Power Loading, Bit Loading, Bit Loading and Water Filling, and Bit and Power Loading strategies are applied.*

stronger when the number of subcarriers is 4 instead of 8. In particular, without equalization, the curves are very steep and there is a penalty of 3 dB already passing through 2 cascaded WSS, for all the considered power ratio strategies. Considering equalization, curves are less steep, but penalties are still unacceptable when 7 WSS are cascaded. The best configurations based on theoretical power ratios for bit loading and bit and power loading strategies are reported in Table 3.17. Those related to bit loading and water filling in Table 3.18, but for 7 cascaded WSS and actual WSS filtering without equalization the value of SNR is not acceptable and it not possible to determine the best constellation.

HD-FEC When HD-FEC technique is used (Figure 3.18), when the filter is the approximated WSS one, penalties between having 0 WSS and 7 WSS is less than 2 dB for all the applied power ratio strategies. If the filter is the actual/real WSS filter and equalization is not performed, 3 dB penalty is obtained starting from 3 cascaded WSS. In case of bit loading and water filling strategy, the required SNR is lower when the cascaded WSS are 4 than when they are 3. This means that the configuration selected as the best one actually is not the best for 3 WSS and actual WSS filtering without equalization, but it must exists another one which requires a lower SNR. In fact, looking at the best modulations reported in Table 3.19, in the column in the center it is possible to see that the constellation used for 3 WSS is [16 16 16 16], whereas the constellation used for 4 WSS is [8 32 32 8], which could be the best also for 3 WSS. This result suggests an analysis with optimized power

N_{WSS}	Modulation Format per SC		
	Approx. WSS filter No equalization	*Actual/real WSS filter No equalization*	*Actual/real WSS filter Equalization*
0	16 16 16 16	16 16 16 16	16 16 16 16
1	16 16 16 16	16 16 16 16	16 16 16 16
2	16 16 16 16	16 16 16 16	16 16 16 16
3	16 16 16 16	16 16 16 16	16 16 16 16
4	16 16 16 16	8 32 32 8	16 16 16 16
5	16 16 16 16	8 32 32 8	8 32 32 8
6	8 32 32 8	8 32 32 8	8 32 32 8
7	8 32 32 8	8 32 32 8	8 32 32 8

Table 3.17: Best modulation formats based on theoretical power ratios for 4x8 GBaud SCM signal when Bit Loading and Bit and Power Loading stategies are used with SD-FEC technique in a lumped noise at the receiver scenario.

N_{WSS}	Modulation Format per SC		
	Approx. WSS filter No equalization	*Actual/real WSS filter No equalization*	*Actual/real WSS filter Equalization*
0	16 16 16 16	16 16 16 16	16 16 16 16
1	16 16 16 16	16 16 16 16	16 16 16 16
2	16 16 16 16	16 16 16 16	16 16 16 16
3	8 32 32 8	8 32 32 8	8 32 32 8
4	8 32 32 8	8 32 32 8	8 32 32 8
5	8 32 32 8	8 32 32 8	8 32 32 8
6	8 32 32 8	8 32 32 8	8 32 32 8
7	8 32 32 8	-	8 32 32 8

Table 3.18: Best modulation formats based on theoretical power ratios for 4x8 GBaud SCM signal when Bit Loading and Water Filling strategy is used with SD-FEC technique in a lumped noise at the receiver scenario.

ratios.

In case of equalization, the behaviour of the curve is very similar to the curve obtained for approximated WSS filtering (theoretical behaviour). With 7 WSS, the largest penalty of using actual WSS filter without equalization over approximated WSS filter when bit loading strategy is used is almost 2 dB, a negligible value compared to the one given in case of SD-FEC. This means that, when HD-FEC technique and equalization are used, the system is more robust than SD-FEC to filtering effects of actual WSS filtering for an increasing number of cascaded WSS.

SD-FEC vs HD-FEC From these results, it is clear that for both SD-FEC and HD-FEC, in case of actual WSS filtering, which is the filter used in reality, equalization is mandatory to obtain good and acceptable values of required SNR. Comparing SD-FEC and HD-FEC, for HD-FEC, there is not such a big variation of optimal modulation formats for bit loading and bit and power loading strategies, because the curves are less steep and the variation of required SNR for increasing number of cascaded WSS is smaller than in

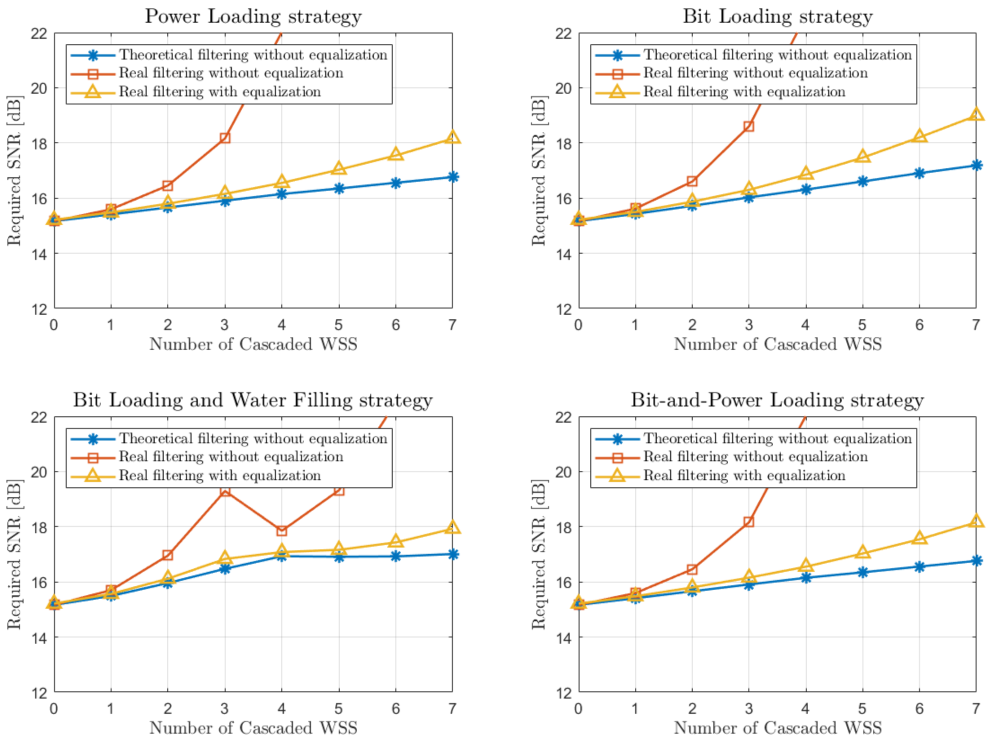


Figure 3.18: *Required SNR vs Number of Cascaded WSS for lumped noise at the receiver in case of 4x8 GBaud SCM signal and HD-FEC when Power Loading, Bit Loading, Bit Loading and Water Filling, and Bit and Power Loading strategies are applied.*

N_{WSS}	**Modulation Format per SC**		
	Bit Loading strategy	*Bit loading and Water Filling strategy*	*Bit and Power Loading strategy*
0	16 16 16 16	16 16 16 16	16 16 16 16
1	16 16 16 16	16 16 16 16	16 16 16 16
2	16 16 16 16	16 16 16 16	16 16 16 16
3	16 16 16 16	16 16 16 16	16 16 16 16
4	16 16 16 16	8 32 32 8	16 16 16 16
5	16 16 16 16	8 32 32 8	16 16 16 16
6	16 16 16 16	8 32 32 8	16 16 16 16
7	16 16 16 16	8 32 32 8	16 16 16 16

Table 3.19: Best modulation formats based on theoretical power ratios for 4x8 GBaud SCM signal when Bit Loading, Bit Loading and Water Filling and Bit and Power Loading strategies are used with HD-FEC technique in a lumped noise at the receiver scenario. Each column is referred to approximated WSS filtering, actual WSS filtering without equalization and actual WSS filtering with equalization.

SD-FEC.

From Figure 3.19, SD-FEC results in lower required SNRs than HD-FEC, when the

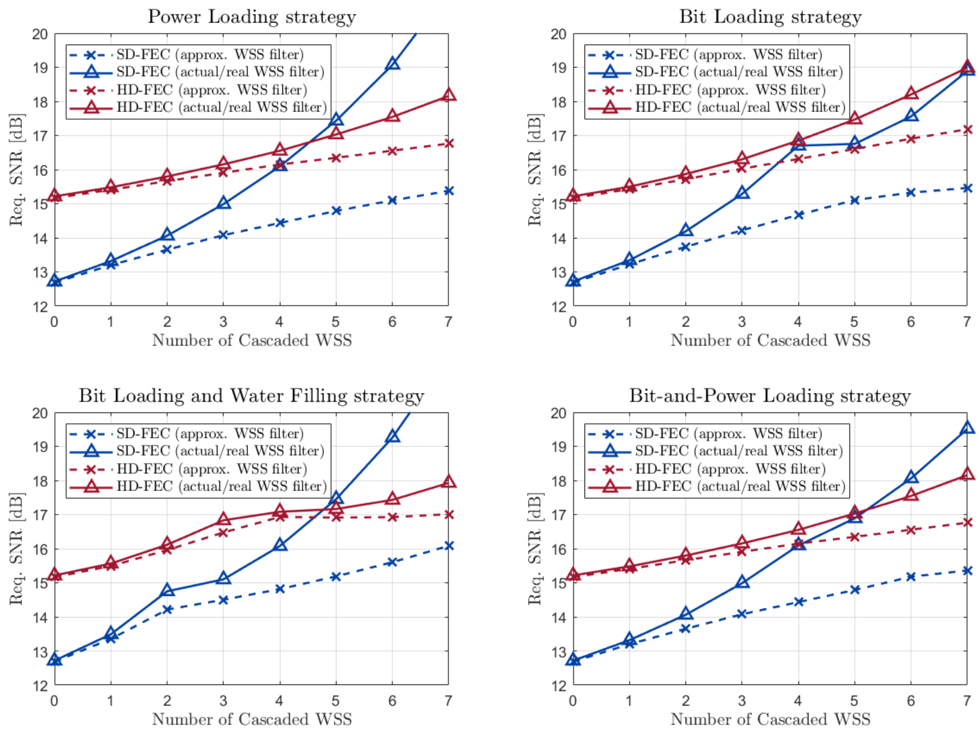


Figure 3.19: *Comparison between SD-FEC and HD-FEC in terms of Required SNR vs Number of Cascaded WSS for 4x8 GBaud SCM signal and lumped noise at RX when different power ratio strategies are applied. Actual WSS filtering is with equalization.*

approximated WSS filter is used, i.e. for an ideal scenario. Instead, considering a realistic scenario, for which the filter is the actual/real WSS filter, at a certain number of cascaded WSS, the use of HD-FEC provides better performance. This happens in case of power loading, bit loading and water filling and bit and power loading strategies, but it is not true for single bit loading strategy, at least up to 7 cascsded WSS.

Lumped noise at the receiver: bit and power loading optimization based on optimized power ratios

As for 8 subcarriers, let us perform the optimization in case of SD-FEC technique considering the constellations of Table 3.16. Their required SNRs are obtained applying bit and power loading with the optimized values of power ratios and among them, for each number of cascaded WSS, the modulation format requiring the lowest SNR is selected, resulting in the black dashed lines in Figure 3.20. The red dashed lines instead represent the performance of the system when bit and power loading is performed based on the theoretical power ratios.

When equalization is not used (picture on the left), the red curve completely diverges from the black one. This means that bit and power loading based on theoretical power ratios do not provide the optimal power ratios to find the best constellations. The best

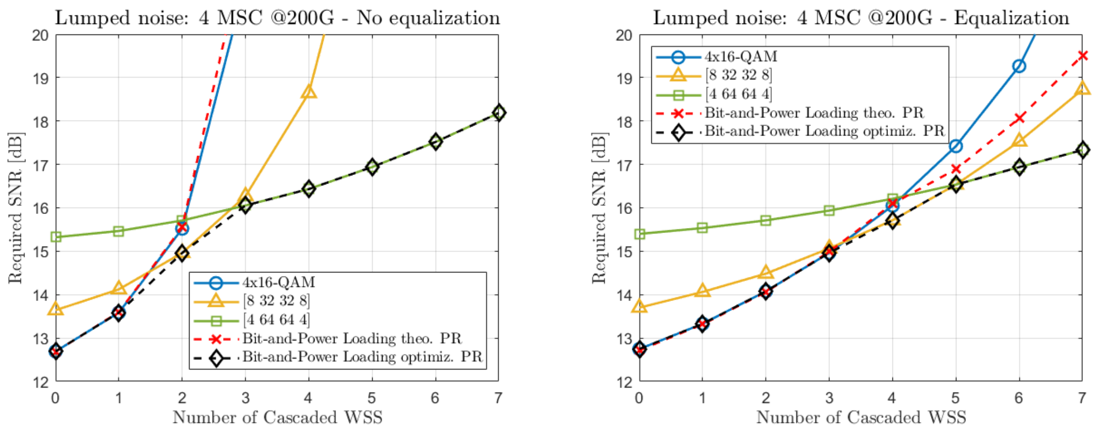


Figure 3.20: *Best constellations, bit and power loading based on theoretical PRs (red dashed line) and bit and power loading based on optimized PRs (black dashed line) without equalization (on the left) and with equalization (on the right) for a 4x8GBaud SCM signal and noise lumped at the receiver.*

N_{WSS}	**Modulation Format per SC**	
	Bit and Power Loading based on theoretical PRs	*Bit and Power Loading based on optimized PRs*
0	16 16 16 16	16 16 16 16
1	16 16 16 16	16 16 16 16
2	16 16 16 16	8 32 32 8
3	16 16 16 16	4 64 64 4
4	8 32 32 8	4 64 64 4
5	8 32 32 8	4 64 64 4
6	8 32 32 8	4 64 64 4
7	8 32 32 8	4 64 64 4

Table 3.20: Best modulation formats for Bit and Power Loading based on theoretical power ratios, in column on the left, and based on optimized power ratios, in column on the right, for 4x8 GBaud SCM signal and SD-FEC technique *without equalization* in a lumped noise at the receiver scenario.

modulation formats determined by the two approches are highlighted in Table 3.20: only for 0 and 1 WSS the choices are the same, and this explains why the performance are so different. This can be seen also by looking at the power ratios in Table 3.21, whose values are similar only when there is no WSS or only one.

By using the optimized power ratios, system performance improves, in fact the penalty between 0 WSS and 7 WSS is just a little bit more than 5 dB, which is however significative.

If equalization is applied (Figure 3.20 on the right), the behaviour of the red curve is not so different from the black curve, since the penalty between the two curves is about 2 dB. On the other hand, the penalty between the required SNRs in case of 0 WSS and in case of 7 WSS do not reduce so much with respect to the scenario without equalization, thus

N_{WSS}	Theoretical PRs per SC [dB]				Optimized PRs per SC [dB]			
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.3	-0.3	-0.3	0.3	0.3	-0.5	-0.5	0.3
2	0.6	-0.7	-0.7	0.6	-1.2	1.0	1.0	-1.2
3	1.0	-1.2	-1.2	1.0	-5.1	2.0	2.0	-5.1
4	-2.0	1.3	1.3	-2.0	-3.8	2.0	2.0	-3.8
5	-1.5	1.1	1.1	-1.5	-3.5	1.7	1.7	-3.5
6	-1.3	1.0	1.0	-1.3	-2.9	1.7	1.7	-2.9
7	0.7	-0.9	-0.9	0.7	-2.8	1.6	1.6	-2.8

Table 3.21: Theoretical and optimized power ratios for Bit and Power Loading applied to a 4x8 GBaud MSC signal *without equalization* in a lumped noise at the receiver scenario.

N_{WSS}	Modulation Format per SC	
	Bit and Power Loading based on theoretical PRs	*Bit and Power Loading based on optimized PRs*
0	16 16 16 16	16 16 16 16
1	16 16 16 16	16 16 16 16
2	16 16 16 16	16 16 16 16
3	16 16 16 16	16 16 16 16
4	16 16 16 16	8 32 32 8
5	8 32 32 8	4 64 64 4
6	8 32 32 8	4 64 64 4
7	8 32 32 8	4 64 64 4

Table 3.22: Best modulation formats for Bit and Power Loading based on theoretical power ratios, in column on the left, and based on optimized power ratios, in column on the right, for 4x8 GBaud SCM signal and SD-FEC technique *with equalization* in a lumped noise at the receiver scenario.

there is not such a big improvement when equalization is used. Now the best modulation formats in case of theoretical power ratios and in case of optimized ones are the same up to 3 cascaded WSS, as shown in Table 3.22. This is visible also by looking at their values in Table 3.23, where they are pretty similar only up to 3 WSS. In general, when there are more than 1 cascaded WSS and bit and power loading is applied using the optimized power ratios, the gain of using equalization over not using it is about 1 dB.

Equally distributed noise

Let us consider the equally distributed noise scenario and theoretical power ratios. As already obtained in case of 8 subcarriers, required SNRs have lower values when the noise is equally distributed instead of having the noise lumped at the receiver, since now noise is filtered span by span.

The used power ratio strategies are still power loading, bit loading, bit loading and water filling and bit and power loading, as depicted in Figure 3.21. At a first glance, they seem to provide more or less the same performance in terms of required SNR, in particular in case of approximated WSS filtering without equalization and actual/real WSS filtering

N_{WSS}	Theoretical PRs per SC [dB]				Optimized PRs per SC [dB]			
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.3	-0.3	-0.3	0.3	0.4	-0.2	-0.2	0.4
2	0.5	-0.6	-0.6	0.5	0.7	-0.9	-0.9	0.7
3	0.7	-0.9	-0.9	0.7	1.0	-1.3	-1.3	1.0
4	0.9	-1.2	-1.2	0.9	-0.5	0.3	0.3	-0.5
5	-1.1	0.9	0.9	-1.1	-3.4	1.7	1.7	-3.4
6	-1.0	0.8	0.8	-1.0	-2.8	1.6	1.6	-2.8
7	-0.8	0.7	0.7	-0.8	-2.7	1.6	1.6	-2.7

Table 3.23: Theoretical and optimized power ratios for Bit and Power Loading applied to a 4x8 GBaud MSC signal *with equalization* in a lumped noise at the receiver scenario.

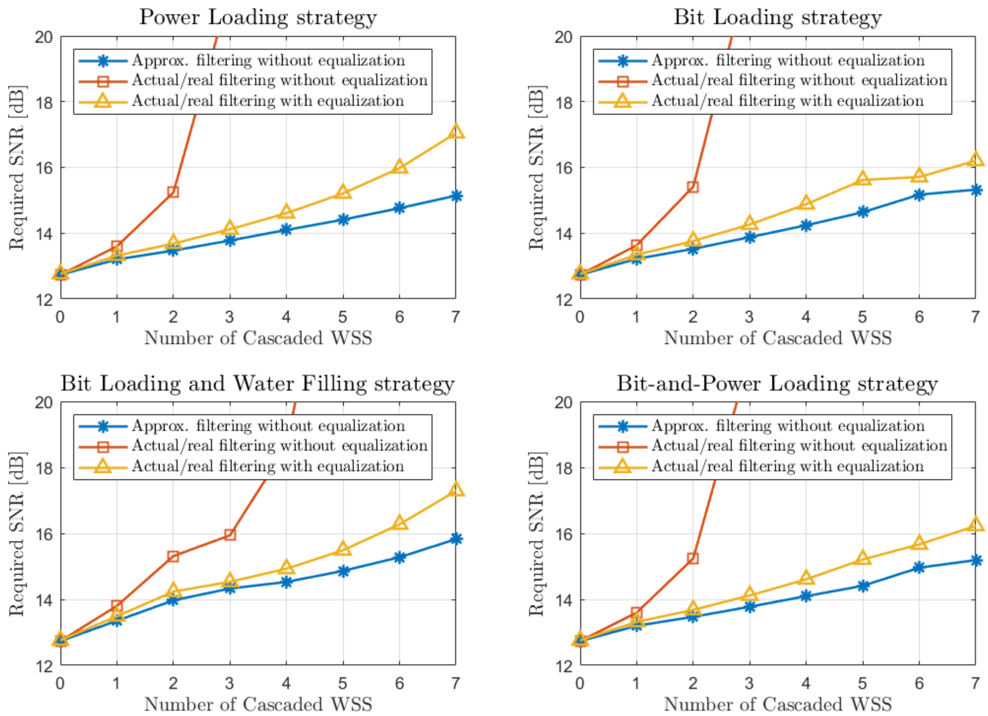


Figure 3.21: *Required SNR vs Number of Cascaded WSS for equally distributed noise in case of 4x8 GBaud SCM signal and SD-FEC when Power Loading, Bit Loading, Bit Loading and Water Filling, and Bit and Power Loading strategies are applied.*

with equalization. The biggest difference in performance is when bit loading and water filling strategy is applied with actual/real WSS filtering without equalization, for which the curve is less steep than for the other strategies. In fact, at 3 WSS, the penalty is 3 dB, which is already significative, but at least it does not explode as for the other three strategies.

Whether for actual WSS filtering without equalization curves grow exponentially, for approximated WSS filtering and actual WSS filtering with equalization, curves are pretty

N_{WSS}	Bit and Power Loading based on optimized PRs	Optimized PRs per SC [dB]			
0	16 16 16 16	0.0	0.0	0.0	0.0
1	16 16 16 16	0.3	-0.3	-0.5	0.3
2	8 32 32 8	-1.8	1.2	1.2	-1.8
3	4 64 64 4	-5.3	2.1	2.1	-5.3
4	4 64 64 4	-5.0	2.0	2.0	-5.0
5	4 64 64 4	-4.4	2.0	2.0	-4.4
6	4 64 64 4	-3.8	2.0	2.0	-3.8
7	4 64 64 4	-3.8	2.0	2.0	-3.8

Table 3.24: Best modulation formats and optimized power ratios for Bit and Power Loading applied to a 4x8 GBaud MSC signal *without equalization* in an equally distributed noise scenario.

linear. Best performance is obtained for bit and power loading, as expected, for which the penalty between having 0 WSS and having 7 WSS is 2.5 dB, in case of approximated WSS, and 3.5 dB, in case of actual WSS with equalization. Up to 3 cascaded WSS, the blue curve could be a good approximation of the yellow one, but not for more WSS, since the penalty between the two is higher, resulting in a degradation of performace. As instance, for power loading strategy at 7 WSS, which is the worst case among the four strategies, the penalty is 2 dB.

Equally distributed noise: bit and power loading optimization based on optimized power ratios

When optimized power ratios are used to perform optimization of bit and power loading strategy without equalization, performance significantly improve with respect to performance obtained when bit and power loading is performed using theoretical power ratios, as shown in Figure 3.22 on the left. Therefore, in this case optimization is necessary and the best configurations and their power ratios are reported in Table 3.24. Instead, when equalization is used, the two curves almost perfectly overlap, thus theoretical power ratios, even if computed for noise lumped at the receiver, are enough to evaluate the required SNR for a given number of cascaded WSS, without performing the optimization, which is time consuming. Best modulation formats and relative optimized power ratios in case of equalization are shown in Tables 3.25 and 3.26. Best constellations based on theoretical power ratios and based on optimized power ratios are different only for 5 and 7 WSS, affecting the values of power ratios, which are quite different for these two cases. For all the other possible numbers of cascaded WSS, values of power ratios are very similar.

3.2.4 16 subcarriers

In this section the simulation study is concluded by considering 16 subcarriers, for which the compexity at the encoder and at the decoder is higher than for a smaller number of subcarriers, since simulations take longer to complete. The costellations providing 200G net capacity are those reported in Table 3.27. Here, constellations including PM-64QAM are not taken into account because their poor performance is already known.

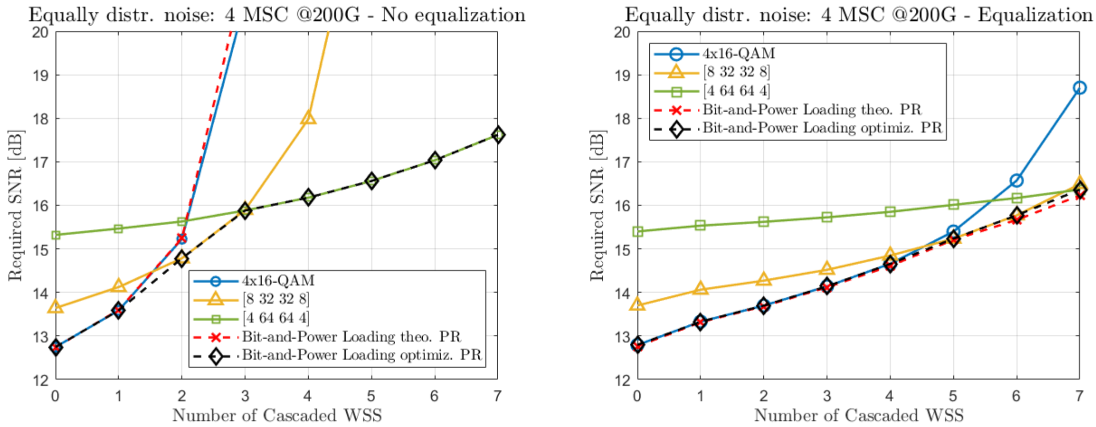


Figure 3.22: *Best constellations, Bit and Power Loading based on theoretical PRs (red dashed line) and Bit and Power Loading based on optimized PRs (black dashed line) without equalization (on the left) and with equalization (on the right) for a 4x8GBaud SCM signal and equally distributed noise.*

$\mathbf{N_{WSS}}$	**Modulation Format per SC**	
	Bit and Power Loading based on theoretical PRs	*Bit and Power Loading based on optimized PRs*
0	16 16 16 16	16 16 16 16
1	16 16 16 16	16 16 16 16
2	16 16 16 16	16 16 16 16
3	16 16 16 16	16 16 16 16
4	16 16 16 16	16 16 16 16
5	16 16 16 16	8 32 32 8
6	8 32 32 8	8 32 32 8
7	8 32 32 8	4 64 64 4

Table 3.25: Best modulation formats for Bit and Power Loading based on theoretical power ratios, in column on the left, and based on optimized power ratios, in column on the right, for 4x8 GBaud SCM signal and SD-FEC technique *with equalization* in an equally distributed noise scenario .

Lumped noise at the receiver

As already done in case of 4 and 8 subcarriers, simulations are performed first applying SD-FEC, then applying HD-FEC.

SD-FEC As depicted in Figure 3.23, required SNR trend related to actual WSS filtering both without and with equalization perfectly follows the trend related to approximated filtering, except for power loading strategy with actual WSS filtering without equalization. In case of power loading, the used modulation format is always the 16x16QAM and it is better to perform equalization when cascaded WSS are 5 or more, because the penalty between the SNR required in case of actual WSS filtering without equalization and the one required in case of approximated WSS filtering is 1.3 dB at 5 cascaded WSS.

N_{WSS} N_{WSS}	Theoretical PRs per SC [dB]				Optimized PRs per SC [dB]			
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.3	-0.3	-0.3	0.3	0.4	-0.2	-0.2	0.4
2	0.5	-0.5	-0.5	0.5	0.5	-0.5	-0.5	0.5
3	0.6	-0.8	-0.8	0.6	0.7	-0.7	-0.7	0.7
4	0.8	-1.0	-1.0	0.8	0.8	-1.0	-1.0	0.8
5	1.0	-1.2	-1.2	1.0	-1.1	0.7	0.7	-1.1
6	-0.8	0.7	0.7	-0.8	-0.7	0.5	0.5	-0.7
7	-0.7	0.6	0.6	-0.7	-3.8	2.0	2.0	-3.8

Table 3.26: Theoretical and optimized power ratios for Bit and Power Loading applied to a 4x8 GBaud MSC signal *with equalization* in an equally distributed noise scenario.

16x2 GBaud Modulation formats
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
8 8 16 16 16 16 32 32 32 32 16 16 16 16 8 8
8 8 8 16 16 32 32 32 32 32 32 16 16 8 8 8
8 8 8 8 32 32 32 32 32 32 32 32 8 8 8 8
4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
4 8 8 16 32 32 32 32 32 32 32 32 16 8 8 4
4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
4 4 8 32 32 32 32 32 32 32 32 32 32 8 4 4

Table 3.27: Modulation formats using 16 MSC providing 200G net capacity.

For bit loading and water filling strategy, the required SNR increases linearly up to 5 cascaded WSS, then exponentially, resulting in the worst strategy among the four in terms of required SNR for an increasing number of cascaded WSS. The best modulation formats based on theoretical power ratios obtained in case of lumped noise at the receiver are reported in Table 3.28.

Instead, for bit loading and bit and power loading strategies, required SNR grows linearly and the penalty at 7 WSS between the required SNR of actual WSS filtering without equalization and the one of approximated WSS filtering is less than 1 dB. Therefore, they are the strategies providing the best performance, in particular bit and power loading, for which the penalty between having 0 WSS and having 7 WSS is less than 4 dB. Their best modulation formats are respectively reported in Tables 3.29 and 3.30.

Except for power loading strategy with more than 4 cascaded WSS, there is no need to perform equalization if the actual/real WSS filtering is used. In case of bit loading, bit loading and water filling, and bit and power loading strategies, system performance can be simulated by just using the approximated WSS filter without equalization, because, as already highlighted, the penalty with respect to the SNRs required when the actual WSS filter is used (without and with equalization), is negligible. This is not valid in case of simple power loading.

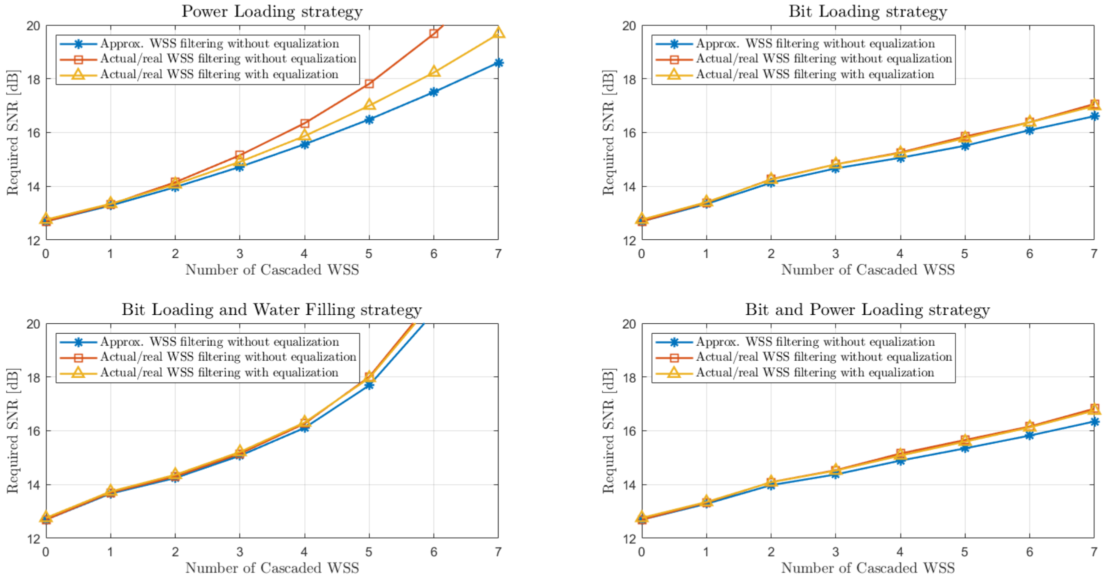


Figure 3.23: *Required SNR vs Number of Cascaded WSS for lumped noise at the receiver in case of 16x2 GBaud SCM signal and SD-FEC when Power Loading, Bit Loading, Bit Loading and Water Filling, and Bit and Power Loading strategies are applied.*

N_{WSS}	**Modulation Format per SC** *BL & WF strategy based on theoretical PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
2	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
3	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
4	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
5	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
6	4 4 8 32 32 32 32 32 32 32 32 32 32 8 4 4
7	4 4 8 32 32 32 32 32 32 32 32 32 32 8 4 4

Table 3.28: Best modulation formats for Bit Loading and Water Filling strategy based on theoretical power ratios for 16x2 GBaud SCM signal and SD-FEC technique in a lumped noise at the receiver scenario.

HD-FEC Also when HD-FEC technique is used (Figure 3.24), for all the four strategies, the system can be studied just performing simulations using the approximated WSS filtering without equalization, which models the theory. When power loading strategy is applied with the actual WSS filter without equalization, this is valid only up to 4 cascaded WSS, because, if the number of WSS is larger, the penalty with respect to the blue curve, is too high. Whereas, it is always true if equalization is performed. In case of bit loading and actual WSS filtering without equalization, the required SNRs are lower with 6 and 7 cascaded WSS than with 5 WSS, because the strategy performs a better choice in terms of best modulation format based on theoretical power ratios. It means that, passing through 5 WSS, the signal could be modulated by a constellation requiring a lower SNR.

N_{WSS}	**Modulation Format per SC** *BL strategy based on theoretical PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
5	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 3.29: Best modulation formats for Bit Loading strategy based on theoretical power ratios for 16x2 GBaud SCM signal and SD-FEC technique in a lumped noise at the receiver scenario.

N_{WSS}	**Modulation Format per SC** *BPL strategy based on theoretical PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
5	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 3.30: Best modulation formats for Bit and Power Loading strategy based on theoretical power ratios for 16x2 GBaud SCM signal and SD-FEC technique in a lumped noise at the receiver scenario.

In general, all the curves grow linearly, but with different slopes. Best performance is obtained for bit loading and bit and power loading, for which the slope is less steep; in fact, the difference between the required SNRs when there are 0 WSS and when there are 7 WSS is less than 2 dB. The modulation format used when power loading is performed is always 16x16QAM, regardless the number of cascaded WSS. Instead, the optimal modulation formats based on theoretical power ratios in case of bit loading, bit loading and water filling and bit and power loading are respectively reported in Tables 3.31, 3.32 and 3.33.

SD-FEC vs HD-FEC In Figure 3.25, in case of power loading, solid lines are related to the actual WSS filtering with equalization, instead for the other three power ratio strategies, solid lines are obtained without equalization, which is not needed to get low required SNR when the filter is the actual WSS filter. Moreover, it is possible to see that in case of simple power loading, when more than 5 WSS are cascaded, it is better to use HD-FEC technique instead of SD-FEC. The same in case of bit loading and water filling strategy when the cascaded WSS are more than 4. Whereas, in case of bit loading and bit and power loading, up to 7 cascaded WSS, the required SNR is always characterized by lower values when SD-FEC technique is used instead of HD-FEC. Therefore, best performance

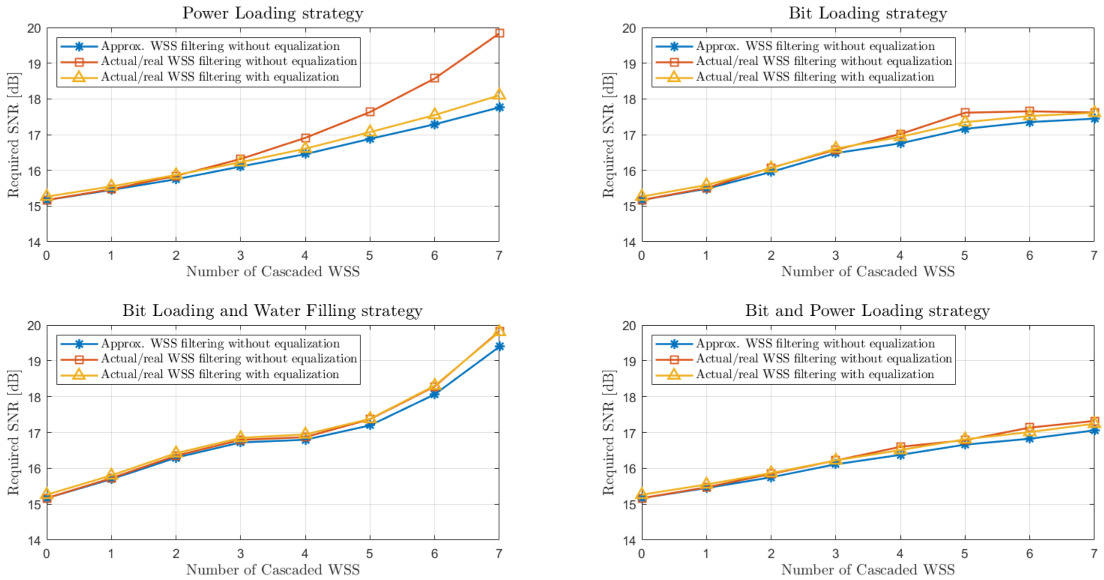


Figure 3.24: *Required SNR vs Number of Cascaded WSS for lumped noise at the receiver in case of 16x2 GBaud SCM signal and HD-FEC when Power Loading, Bit Loading, Bit Loading and Water Filling, and Bit and Power Loading strategies are applied.*

NWSS	**Modulation Format per SC** *BL & WF strategy based on theoretical PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
3	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
4	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
5	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
6	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
7	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4

Table 3.31: Best modulation formats for Bit Loading strategy based on theoretical power ratios for 16x2 GBaud SCM signal and HD-FEC technique in a lumped noise at the receiver scenario.

are obtained when SD-FEC technique is applied and bit and power loading is performed.

Lumped noise at the receiver: bit and power loading optimization based on optimized power ratios

The optimization of bit and power loading is performed considering the constellations of Table 3.27 only applying SD-FEC technique, since the required SNRs are lower, and assuming actual WSS filtering, to see the effect of a realistic filter on a system with an increasing number of cascaded WSS. It is important to understand whether this optimization is always necessary or theoretical power ratios are enough to get a good description

N_{WSS}	**Modulation Format per SC** *BL & WF strategy based on theoretical PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
5	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4

Table 3.32: Best modulation formats for Bit Loading and Water Filling strategy based on theoretical power ratios for 16x2 GBaud SCM signal and HD-FEC technique in a lumped noise at the receiver scenario.

N_{WSS}	**Modulation Format per SC** *BPL strategy based on theoretical PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
3	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
4	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
5	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
6	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
7	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4

Table 3.33: Best modulation formats for Bit and Power Loading strategy based on theoretical power ratios for 16x2 GBaud SCM signal and HD-FEC technique in a lumped noise at the receiver scenario.

of system behaviour. The comparison between the performance obtained when bit and power loading is performed with theoretical power ratios and when bit and power loading is performed with optimized power ratios is shown in Figure 3.26, both without and with equalization. As already discussed in the previous paragraph, equalization is not necessary, but to provide a more complete study, simulations with actual WSS filtering with equalization are performed as well.

Considering the case without equalization, the black dashed line, related to bit and power loading with optimized power ratios, almost perfectly overlap the red dashed line, related to bit and power loading with theoretical power ratios. This means that, to study the system in a scenario with noise lumped at the receiver when the signal is transmitted over 16 subcarriers with 200G rate constraint, theoretical power ratios are able to give a good evaluation of the required SNR to get the target BER (in this case $2 \cdot 10^{-2}$, the one set by SD-FEC techinique). The same considerations can be done if equalization is applied. In fact, as expected, the required SNRs, when equalization is not used, are the same as those required in case of equalization, or, if not exactly the same, the penalty is so small that can be assumed to be negligible. Moreover, when equalization is performed, the curve of bit and power loading based on optimized power ratios is slightly above the

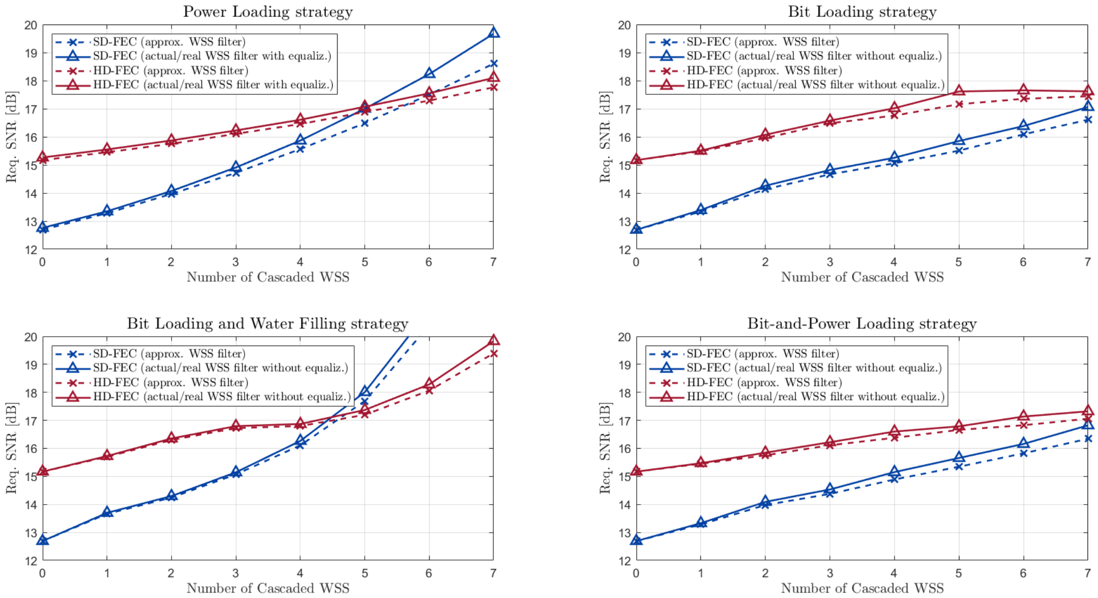


Figure 3.25: *Comparison between SD-FEC and HD-FEC in terms of Required SNR vs Number of Cascaded WSS for 16x2 GBaud SCM signal and lumped noise at the receiver when different power ratio strategies are applied.*

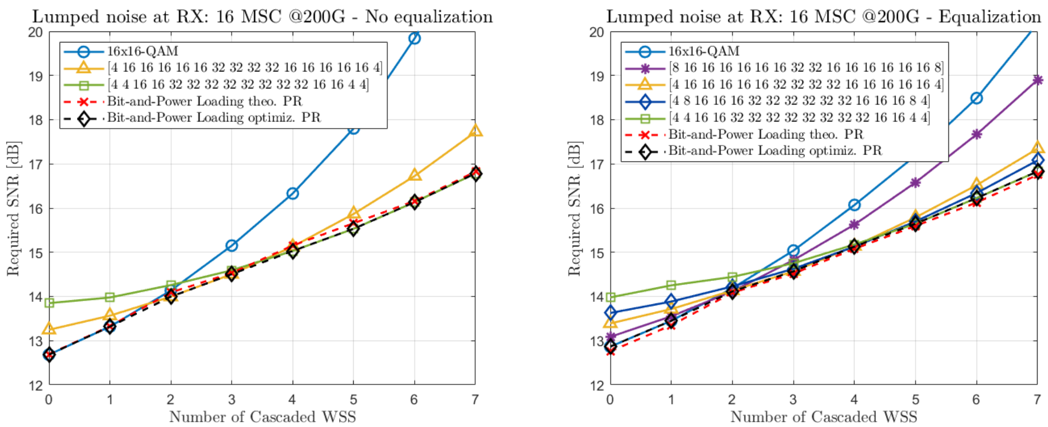


Figure 3.26: *Best constellations, Bit and Power Loading based on theoretical PRs (red dashed line) and Bit and Power Loading based on optimized PRs (black dashed line) without equalization (on the left) and with equalization (on the right) for a 16x2GBaud SCM signal and lumped noise at the receiver.*

curve of bit and power loading based on theoretical power ratios. This can be explained by the fact that, in *fminsearch* function, when the number of subcarrier increases, errors due to non-linear effects increases as well. Nevertheless, this penalty is so small that the obtained curves correspond to the expected ones.

The best modulation formats obtained following the optimization are reported in Tables

N_{WSS}	**Modulation Format per SC** *BPL strategy based on optimized PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
5	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 3.34: Best modulation formats for Bit and Power Loading strategy based on optimized power ratios for 16x2 GBaud SCM signal without equalization and SD-FEC technique in a lumped noise at the receiver scenario.

N_{WSS}	**Modulation Format per SC** *BPL strategy based on optimized PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
5	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 3.35: Best modulation formats for Bit and Power Loading strategy based on optimized power ratios for 16x2 GBaud SCM signal with equalization and SD-FEC technique in lumped noise at the receiver scenario.

3.34 and 3.35, respectively related to the case without equalization and with equalization. Only for 4 cascaded WSS the choice of the optimal modulation format is different: [4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4] is the best without equalization, instead, [4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4] is the best with equalization.

Since performance of WSS filtering without equalization obtained applying bit and power loading strategy with theoretical power ratios and with optimized power ratios are almost the same, it is interesting to see which is their difference in terms of best modulation formats and power ratio values. By comparing Table 3.30, related to theoretical power ratios, and Table 3.34, related to optimized power ratios, best modulation formats are different in case of 2, 4 and 5 cascaded WSS. When the cascaded WSS are 2, the best modulation format in case of theoretical power ratios is [8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8], and in case of optimized power ratios is [4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4]. In case of 5 and 6 cascaded WSS, [4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4] is the best modulation format when theoretical power ratios are used, and [4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4] is the best in case of optimized power ratios. For what concerns power ratios, the theoretical values are reported in Tables 3.36 and 3.37, and the optimized values in Tables 3.38 and 3.39. In general, comparing Tables 3.36 and 3.38,

N_{WSS}	Power Ratio per SC [dB] *BPL strategy*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	1.0	0.3	-0.1	-0.2	-0.3	-0.3	-0.3	-0.3
2	0.6	0.6	-0.2	-0.6	-0.7	-0.8	-0.8	1.4
3	-1.5	1.0	-0.2	-0.7	-0.9	-1.0	1.2	1.2
4	-0.5	-0.2	-0.2	-1.0	-1.3	0.9	0.9	0.9
5	0.3	0.2	-0.2	-1.2	-1.6	0.6	0.6	0.6
6	1.2	-2.7	-0.1	-1.3	0.6	0.4	0.4	0.4
7	2.0	-2.3	-0.1	-1.5	0.3	0.1	0.1	0.1

Table 3.36: Theoretical power ratios of subcarriers from 1 to 8 for Bit and Power Loading applied to a 16x2 GBaud MSC signal *without equalization* in lumped noise at the receiver scenario.

N_{WSS}	Power Ratio per SC [dB] *BPL strategy*							
	9	*10*	*11*	*12*	*13*	*14*	*15*	*16*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	0.3	1.0
2	1.4	-0.8	-0.8	-0.7	-0.6	-0.2	0.6	0.6
3	1.2	1.2	-1.0	-0.9	-0.7	-0.2	1.0	-1.5
4	0.9	0.9	0.9	-1.3	-1.0	-0.2	-0.2	-0.5
5	0.6	0.6	0.6	-1.6	-1.2	-0.2	0.2	0.3
6	0.4	0.4	0.4	0.6	-1.3	-0.1	-2.7	1.2
7	0.1	0.1	0.1	0.3	-1.5	-0.1	-2.3	2.0

Table 3.37: Theoretical power ratios of subcarriers from 9 to 16 for Bit and Power Loading applied to a 16x2 GBaud MSC signal *without equalization* in lumped noise at the receiver scenario.

and Tables 3.37 and 3.39, values corresponding to the same number of cascaded WSS and the same subcarrier are similar, except for 2, 4 and 5 cascaded WSS. Power ratios in case of actual WSS filtering with equalization are not reported, but their optimized values are close to those used to perform bit and power loading without equalization.

Equally distributed noise

Also for a 16x2 GBaud signal, the system is studied simulating the equally distributed noise scenario with SD-FEC technique to see which is the impact of filtering effects on a more realistic scenario with respect to having the noise lumped at the receiver, which is a sort of worst case. The resulting SNRs are depicted in Figure 3.27. Only SD-FEC is applied because it is the FEC techinique providing best performance when the noise is lumped at the receiver.

Let us first consider power loading strategy and transmitted signal filtered with the actual WSS filter without applying equalization. As for lumped noise at the receiver, the required SNR increases faster than the SNR required in case of approximated WSS filtering,

N_{WSS}	Power Ratio per SC [dB] *BPL strategy*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.9	0.3	0.1	-0.4	-0.3	-0.3	-0.3	-0.3
2	-2.3	0.9	-0.2	-0.8	-0.8	-0.3	1.4	1.4
3	-1.7	0.8	0.0	-0.7	-0.9	-1.0	1.1	0.8
4	-0.2	-3.4	0.2	-0.5	0.9	0.3	0.7	0.6
5	0.0	-2.5	-0.2	-0.6	0.9	0.5	0.4	0.7
6	1.0	-2.5	0.1	-1.1	0.7	0.5	0.4	0.2
7	1.3	-1.9	0.4	-1.2	0.4	0.3	0.2	-0.1

Table 3.38: Optimized power ratios of subcarriers from 1 to 8 for Bit and Power Loading applied to a 16x2 GBaud MSC signal *without equalization* in lumped noise at the receiver scenario.

N_{WSS}	Power Ratio per SC [dB] *BPL strategy*							
	9	*10*	*11*	*12*	*13*	*14*	*15*	*16*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	-0.3	-0.3	-0.3	-0.3	-0.4	0.1	0.3	0.9
2	1.4	1.4	-0.3	-0.8	-0.8	-0.2	0.9	-2.3
3	0.8	1.1	-1.0	-0.9	-0.7	0.0	0.8	-1.7
4	0.6	0.7	0.3	0.9	-0.5	0.2	-3.4	-0.2
5	0.7	0.4	0.5	0.9	-0.6	-0.2	-2.5	0.0
6	0.2	0.4	0.5	0.7	-1.1	0.1	-2.5	1.0
7	-0.1	0.2	0.3	0.4	-1.2	0.4	-1.9	1.3

Table 3.39: Optimized power ratios of subcarriers from 9 to 16 for Bit and Power Loading applied to a 16x2 GBaud MSC signal *without equalization* in lumped noise at the receiver scenario.

so there is a penalty, which is 3 dB crossing 7 cascaded WSS. Performance is not so bad as in case of 4 subcarriers, but assuming equalization in presence of actual WSS filtering, the system can be studied by just applying the theoretical simplified model, which uses the approximated WSS filter without equalization. In fact, the resulting curves, which grow linearly, almost perfectly overlap (their difference is very small).

As already observed in the lumped noise at the receiver scenario, when bit loading, bit loading and water filling, and bit and power loading strategies are performed, regardless the type of filtering and use of equalization, the curves of required SNR versus the number of cascaded WSS overlap. In case of bit loading and bit and power loading, at 7 cascaded WSS, the values of required SNR are not exactly the same, but the penalty is so small that can be considered negligible. Thanks to these considerations, as in case of power loading, the system can be studied by just applying the approximated WSS filtering. Moreover, bit loading and bit and power loading are the strategies providing the best performance in terms of required SNR, since the penalty between having 0 cascaded WSS and having 7 cascaded WSS is less than 3 dB.

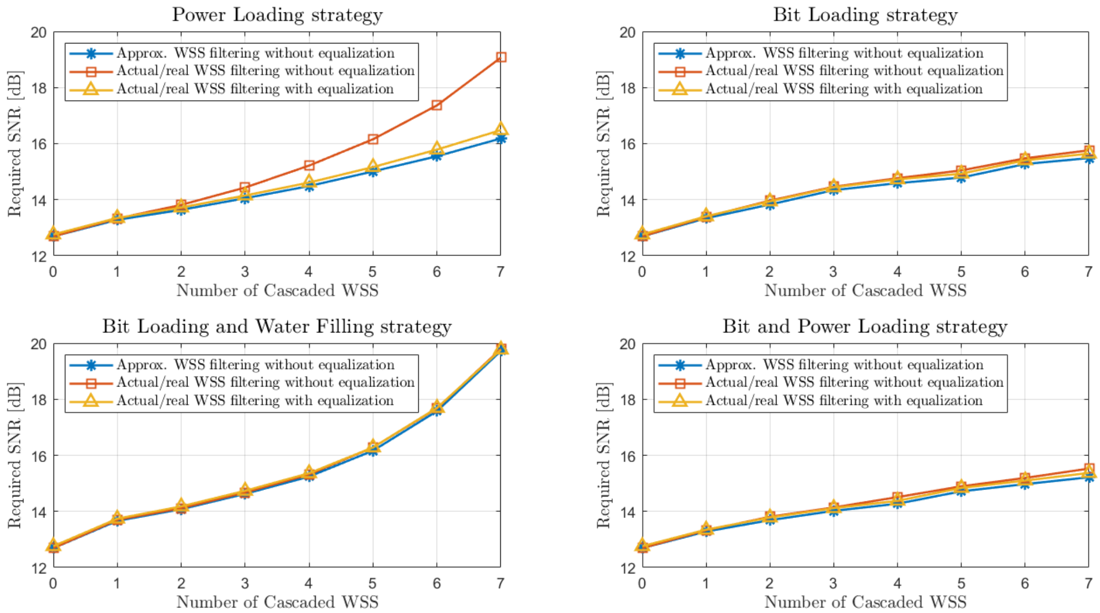


Figure 3.27: *Required SNR vs Number of Cascaded WSS for equally distributed noise in case of 16x2 GBaud SCM signal and SD-FEC when Power Loading, Bit Loading, Bit Loading and Water Filling, and Bit and Power Loading strategies are applied.*

$\mathbf{N_{WSS}}$	**Modulation Format per SC** *BL strategy based on theoretical PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
5	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 3.40: Best modulation formats for Bit Loading strategy based on theoretical power ratios for 16x2 GBaud SCM signal and SD-FEC technique in equally distributed noise scenario.

Based on theoretical power ratios, in case of power loading, the used modulation format is always 16x16QAM regardless the number of cascaded WSS. Instead, for bit loading, bit loading and water filling and bit and power loading strategies, the best modulation formats are reported in Tables 3.40, 3.41 and 3.42. It is important to underline that these constellations do not change for the different types of filtering (approximated WSS filtering without equalization, actual WSS filtering without/with equalization), meaning that the 16x2 GBaud MSC signal is robust to these types of filtering even without equalization.

N_{WSS}	**Modulation Format per SC** *BL & WF strategy based on theoretical PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
2	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
3	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
4	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
5	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
6	4 4 8 32 32 32 32 32 32 32 32 32 32 8 4 4
7	4 4 8 32 32 32 32 32 32 32 32 32 32 8 4 4

Table 3.41: Best modulation formats for Bit Loading and Water Filling strategy based on theoretical power ratios for 16x2 GBaud SCM signal and SD-FEC technique in equally distributed noise scenario.

N_{WSS}	**Modulation Format per SC** *BPL strategy based on theoretical PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
5	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 3.42: Best modulation formats for Bit and Power Loading strategy based on theoretical power ratios for 16x2 GBaud SCM signal with equalization and SD-FEC technique in equally distributed noise scenario.

Equally distributed noise: bit and power loading optimization based on optimized power ratios

The curves shown in Figure 3.28 are obtained in case of actual WSS filtering, both without (on the left) and with (on the right) equalization. As already observed in case of 8 subcarriers, the required SNRs obtained after bit and power loading based on theoretical power ratios (red dashed line), which are computed for lumped noise at the receiver, are very close to those obtained for bit and power loading based on optimized power ratios (black dashed line). Therefore, in case of equally distributed noise, instead of performing optimization of bit and power loading, system performance can be easily evaluated through the model which provides the required SNRs by using constellations and theoretical power ratios computed when noise is lumped at the receiver.

If now bit and power loading strategy based on theoretical and optimized power ratios and a specific number of cascaded WSS are considered, it can be observed that there is no difference in terms of required SNR if equalization is used or not. Instead, power ratios and modulation formats are different, in particular when the number of cascaded WSS increases. For optimized power ratios, best modulation formats are reported in Tables 3.43 and 3.44.

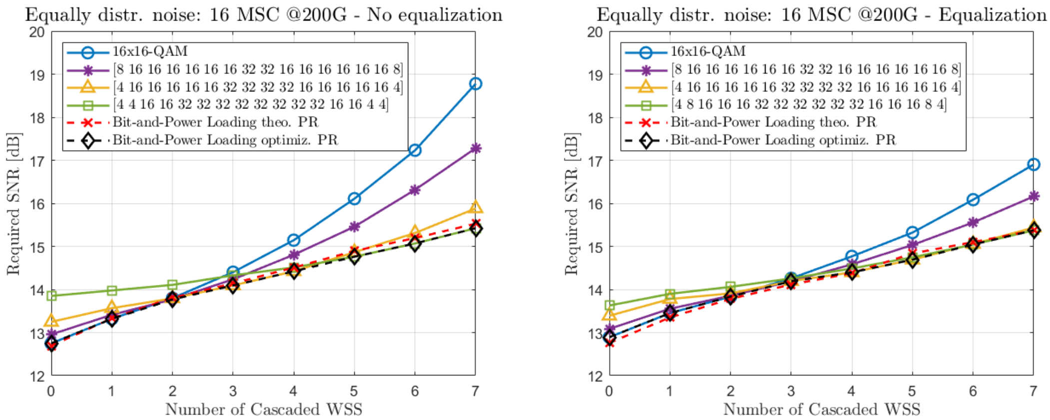


Figure 3.28: *Best constellations, BPL based on theoretical PRs (red dashed line) and BPL based on optimized PRs (black dashed line) without equalization (on the left) and with equalization (on the right) for a 16x2GBaud SCM signal and equally distributed noise.*

$\mathbf{N_{WSS}}$	**Modulation Format per SC** *BPL strategy based on optimized PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
5	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 3.43: Best modulation formats for Bit and Power Loading strategy based on optimized power ratios for 16x2 GBaud SCM signal *without equalization* and SD-FEC technique in equally distributed noise scenario.

This optimization confirms that, also for equally distributed noise, even if the number of cascaded WSS increases, equalization is not needed in case of a 16x2GBaud signal to get low values of SNR. Indeed, the combination of a higher number of subcarriers with bit and power loading are enough to mitigate filtering effects.

Theoretical and optimized power ratios in case of actual WSS filtering without equalization are reported in Tables 3.45-3.48.

3.3 Multi subcarrier modulation with frequency offset

Before proceeding with the validation of simulation results through experiments, it is important to understand which are the effects of laboratory instrumentation on the performance of the system under study. In fact, in simulations, the system is an ideal system,

N_{WSS}	**Modulation Format per SC** *BPL strategy based on optimized PRs*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
3	8 16 16 16 16 16 16 32 32 16 16 16 16 16 16 8
4	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
5	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
6	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
7	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4

Table 3.44: Best modulation formats for Bit and Power Loading strategy based on optimized power ratios for 16x2 GBaud SCM signal *with equalization* and SD-FEC technique in equally distributed noise scenario.

N_{WSS}	**Power Ratio per SC [dB]** *BPL strategy*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	1.0	0.3	-0.1	-0.2	-0.3	-0.3	-0.3	-0.3
2	0.6	0.5	-0.2	-0.6	-0.7	-0.8	-0.8	1.4
3	-1.5	0.9	-0.2	-0.7	-0.9	-1.0	1.2	1.2
4	-0.7	-0.1	-0.2	-0.9	-1.2	0.9	0.9	0.9
5	0.1	-3.0	-0.1	-1.0	0.8	0.7	0.7	0.7
6	0.6	-2.5	-0.1	-1.1	0.7	0.5	0.5	0.5
7	0.9	-2.1	0.0	-1.2	0.5	0.4	0.4	0.3

Table 3.45: Theoretical power ratios of subcarriers from 1 to 8 for Bit and Power Loading applied to a 16x2 GBaud MSC signal *without equalization* in equally distributed noise scenario.

therefore all the effects related on the presence of non-idealities are not taken into account. In particular, it is important to study the effects of a frequency offset on the required SNR. The study is performed only on an 8x4 GBaud MSC signal applying bit loading strategy with SD-FEC technique and varying the frequency offset with a fixed number of WSS in the lumped noise at the receiver scenario. First, the analysis is focused on small frequency offsets, in the order of hundreds of MHz, then on large frequency offsets, in the order of GHz.

It is fundamental to emphasize that each studied modulation format is symmetric, but the insertion of a frequency offset cancels this property of symmetry. For this reason, to understand which is the configuration requiring the lowest SNR for a given number of WSS and a given frequency offset, the study would be more complete if also asymmetric configurations were analysed. This kind of analysis is not reported in this thesis because the purpose of this section is to understand the effects of a frequency offset on a symmetric modulation format, not to find the configuration providing the best performance when a frequency offset is inserted.

N_{WSS}	Power Ratio per SC [dB] *BPL strategy* *9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	0.3	1.0
2	1.4	-0.8	-0.8	-0.7	-0.6	-0.2	0.5	0.6
3	1.2	1.2	-1.0	-0.9	-0.7	-0.2	0.9	-1.5
4	0.9	0.9	0.9	-1.2	-0.9	-0.2	-0.1	-0.7
5	0.7	0.7	0.7	0.8	-1.0	-1.0	-3.0	0.1
6	0.5	0.5	0.5	0.7	-1.1	-0.1	-2.5	0.6
7	0.3	0.4	0.4	0.5	-1.2	0.0	-2.1	0.9

Table 3.46: Theoretical power ratios of subcarriers from 9 to 16 for Bit and Power Loading applied to a 16x2 GBaud MSC signal *without equalization* in equally distributed noise scenario.

N_{WSS}	Power Ratio per SC [dB] *BPL strategy* *1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.9	0.3	0.1	-0.4	-0.3	-0.3	-0.3	-0.3
2	-0.1	0.6	-0.1	-0.5	-0.7	-0.6	-0.6	1.4
3	-2.8	0.3	0.2	-0.4	-0.5	-0.9	1.2	1.5
4	-1.8	0.9	-0.5	-0.6	-0.8	-0.8	1.0	1.3
5	-0.7	-3.5	0.0	-0.1	1.3	1.0	0.7	0.9
6	-0.3	-3.8	0.2	-0.5	1.1	0.8	0.7	1.0
7	0.0	-2.9	-0.1	-0.2	0.8	0.7	0.7	0.ù

Table 3.47: Optimized power ratios of subcarriers from 1 to 8 for Bit and Power Loading applied to a 16x2 GBaud MSC signal *without equalization* in equally distributed noise scenario.

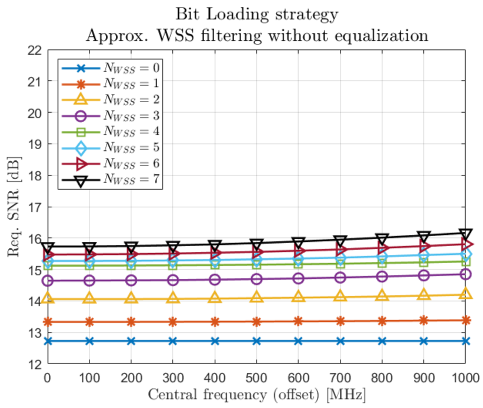
3.3.1 Small frequency offsets

For this study, the number of WSS is kept fixed and the frequency offset varies from 0 MHz to 1 GHz in step of 100 MHz. Figure 3.29 reports the required SNR as a function of the frequency offset when SD-FEC technique is applied. The comparisons are between approximated WSS filtering without equalization and actual WSS filtering with equalization. Actual WSS filter is combined with equalization because, in the experimental setup, the use of the equalizer is provided.

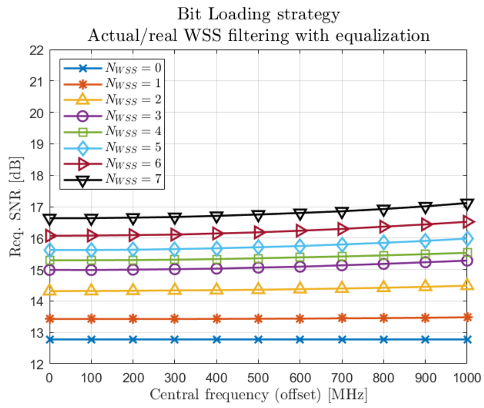
Only SD-FEC is used because from previous simulations it mostly results to be better than HD-FEC in providing low values of SNR. When there are no WSS, the curve is flat because the required SNR is not affected by the increase of the frequency offset. If the number of WSS is higher, also the required SNR increases for increasing frequency offsets, but the penalty between the scenario without WSS and the scenario with 7 WSS is lower than 0.5 dB, hence negligible. Therefore, the best modulation formats per number of cascaded WSS, reported in Table 3.49, do not change if the frequency offset increases. In conclusion, small frequency offset do not impact SNR in a significative way, though 7

N_{WSS}	Power Ratio per SC [dB]							
	BPL strategy							
	9	*10*	*11*	*12*	*13*	*14*	*15*	*16*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	-0.3	-0.3	-0.3	-0.3	-0.4	0.1	0.3	0.9
2	1.4	-0.6	-0.6	-0.7	-0.5	-0.1	0.6	-0.1
3	1.5	1.2	-1.0	-0.5	-0.4	0.2	0.3	-2.8
4	1.2	0.9	0.8	-0.9	-0.6	0.0	-0.9	-1.8
5	0.9	0.7	1.0	1.3	-0.1	0.0	-3.5	-0.7
6	1.0	0.7	0.8	1.1	-0.5	0.2	-3.8	-0.3
7	0.7	0.7	0.7	0.3	-0.2	-0.1	-3.0	0.0

Table 3.48: Optimized power ratios of subcarriers from 9 to 16 for Bit and Power Loading applied to a 16x2 GBaud MSC signal *without equalization* in equally distributed noise scenario.



(a) Approximated WSS filtering without equalization



(b) Actual/real WSS filtering with equalization

Figure 3.29: *Effects of small frequency offsets (in the order of 100s of MHz) for different numbers of cascaded WSS when SD-FEC is applied on an 8x4 GBaud signal.*

cascaded WSS are crossed.

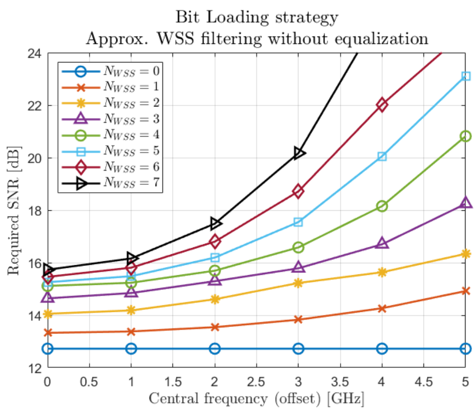
3.3.2 Large frequency offsets

Now let us consider a frequency offset varying from 0 GHz to 5 GHz in steps of 1 GHz, always keeping the number of cascaded WSS fixed. The resulting required SNR are depicted in Figures 3.30a and 3.30b, which respectively refer to approximated WSS filtering without equalization and actual/real WSS filtering with equalization.

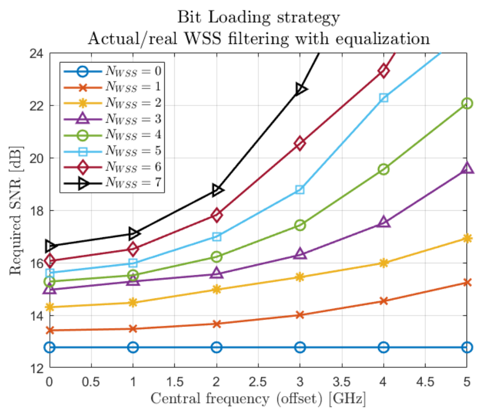
Frequency offset does not affect the SNR when no WSS are present, as expected and demonstrated by the flat curves. On the contrary, the larger the number of cascaded WSS, the higher the penalty for an increasing frequency offset. For instance, while for 1 WSS (blue solid line) and 5 GHz frequency offset the penalty is around 2 dB, for 7 WSS (black

N_{WSS}	**Best modulation formats** *BL strategy*
0	16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16
2	16 16 16 16 16 16 16 16
3	8 16 16 32 32 16 16 8
4	4 16 32 32 32 32 16 4
5	4 16 32 32 32 32 16 4
6	4 16 32 32 32 32 16 4
7	4 16 32 32 32 32 16 4

Table 3.49: Best modulation formats for Bit Loading strategy when a small frequency offset is applied on an 8x4 GBaud SCM signal with SD-FEC technique in lumped noise at the receiver scenario.



(a) Approximated WSS filtering without equalization



(b) Actual/real WSS filtering with equalization

Figure 3.30: *Effects of large frequency offsets (in the order of GHz) for different numbers of cascaded WSS when SD-FEC is applied on an 8x4 GBaud signal.*

solid line) the penalty is approximately 3 dB already with 2 GHz frequency offset.

Fortunately, in reality, frequency offsets do not assume such large values, but they are smaller. In fact, up to 1 GHz offset, SNR penalties are low, so the model is quite robust against small frequency offsets.

Chapter 4

Experimental validation

The previous chapter showed that when subcarriers are 8 or more, the simulated system using WSS filtering can be analytically described by a simplified system which uses the approximated WSS filter, i.e. theory can be applied. Therefore, the experimental results can be compared with the theoretical results, without the need of performing simulations. In this chapter the experimental validation is performed varying the number of subcarriers from 2 to 16 with 200G rate constraint and applying a SD-FEC technique with $2.4 \cdot 10^{-2}$ target BER, which is the maximum value for which commercial FECs are able to compensate for all errors.

The optical back-to-back setup used for this experimental validation is depicted in Figure 4.1 and is the one used in [14]. At the transmitter side, the Arbitrary Waveform

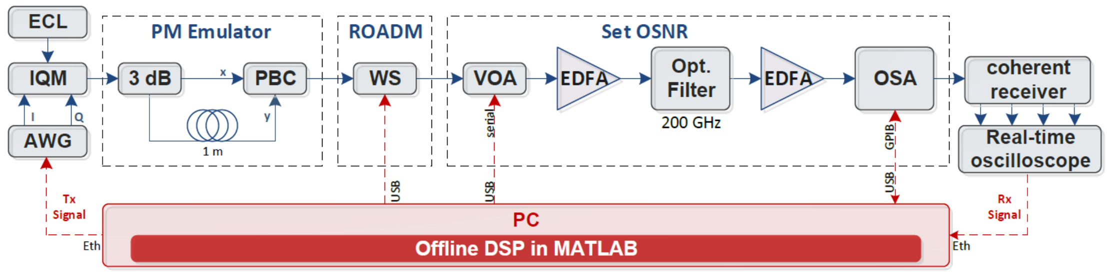


Figure 4.1: *Experimental setup for the optical back-to-back scenario with ROADM filtering emulation.*

Generator (AWG) digitally generates the MSC signal at 64 GSamples/s. To reduce the impact on performance of bandwidth limitation at the trasmitter, it includes digital pre-emphasis. Each sub-carrier is shaped by a root-raised-cosine (RRC) with 0.05 roll-off factor. Then, a single-polarization IQ Modulator (IQM), fed by an External Cavity Laser (ECL), optically upconverts the electrical signal. PM Emulator emulates polarization multiplexing by inserting a delay of about 5 ns, i.e. first attenuating the electrical signal of 3 dB, then propagating the y-polarized signal component along a 1 m long piece of fiber. Afterwards, the two signal components are combined together through a Polarizer Beam Combiner (PBC). The effect of the Reconfigurable Optical Add-Drop Multiplexer (ROADM), i.e. the optical filtering of cascaded WSS, is emulated by a WaveShaper (WS) which implements the transfer function of expression 2.1, whose experimental traces are shown in Figure 4.2. The Variable Optical Attenuator (VOA) and the first Erbium Doped Fiber Amplifier

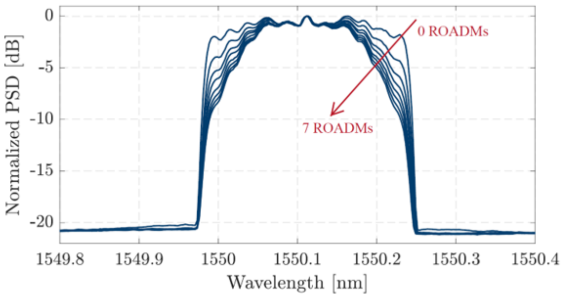


Figure 4.2: *Experimental traces obtained from the OSA after emulation of a different number of cascaded ROADMs.*

(EDFA) are used to perform noise loading, needed to set the operating Optical Signal-to-Noise Ratio (OSNR). The 200 GHz optical filter is placed to remove the out-of-band noise and the second EDFA guarantees a fixed optical power at the input of the coherent receiver. The Optical Spectrum Analyzer (OSA) provides the spectrum from which the OSNR is measured. At the receiver side, after coherent detection, analog to digital conversion (ADC) of the signal is performed with a real-time oscilloscope (50 GSamples/s). Then, the data-offline Digital Signal Processing (DSP) is applied by MATLAB. The data-aided DSP includes an initial Constant Modulus Algorithm (CMA) based adaptive equalizer for pre-convergence (15 taps for single-carrier and 5 taps for SCM) followed by frequency offset removal and Viterbi & Viterbi phase estimation (101 taps). A second adaptive equalizer (51 taps for single-carrier and 15 taps for SCM) based on real-valued Least Mean Square (LMS) is finally applied before symbol decoding and error counting.

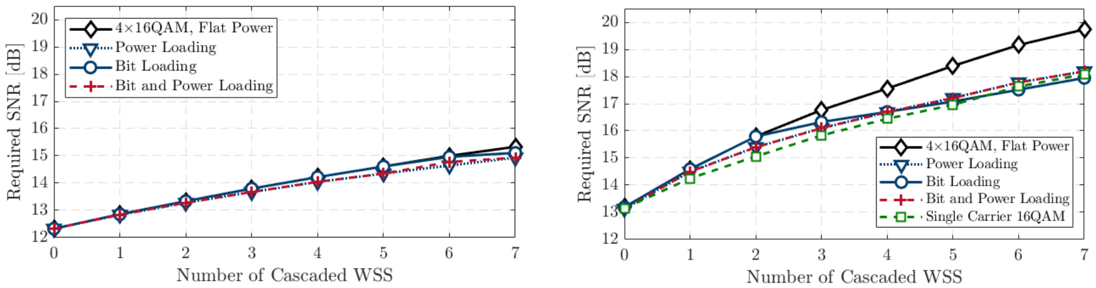
For each number of subcarriers, the modulation formats studied are those already analysed in simulations, which provide a total 200G capacity, but those considering PM-64QAM are excluded, since their performance is alredy known to be bad. For each number of subcarriers, theoretical and experimental results are reported for flat power, power loading, bit loading and bit and power loading. Also best modulation formats and power ratios are reported. The BER strategy in use is not *Same BER* strategy, but *Minimum BER* strategy. In fact, when theoretical analysis is performed, since subcarriers are in parallel and experience different BER, a mean BER is computed and FEC ($2.4 \cdot 10^{-2}$) is applied to this shared BER.

For each number of subcarriers, multi subcarrier experimental results are compared to a single-carrier 32 GBaud PM-16QAM signal, the most common form of modulation for 200G systems, to see whether some advantages are achieved.

4.1 4 subcarriers

Theoretical and experimental results for a 4x8 GBaud transmitted signal are reported in Figure 4.3. Experimental trend for a single-carrier 16QAM signal is shown as well.

Theoretical SNRs are obtained based on optimized constellations and power ratios analytically calculated offline, here presented in Tables 4.1 and 4.2. From Figure 4.3a it results that, theoretically, there is not such a big gain (less than 1 dB) in using power loading,



(a) Theoretical results

(b) Experimental results

Figure 4.3: *Theoretical and experimental required SNR for a 4x8GBaud signal after WSS filtering.*

N_{WSS}	**Modulation Format per SC** *BL strategy*	**Modulation Format per SC** *BPL strategy*
0	16 16 16 16	16 16 16 16
1	16 16 16 16	16 16 16 16
2	16 16 16 16	16 16 16 16
3	16 16 16 16	16 16 16 16
4	16 16 16 16	16 16 16 16
5	16 16 16 16	16 16 16 16
6	8 32 32 8	8 32 32 8
7	8 32 32 8	16 16 16 16

Table 4.1: Best theoretical constellations using Bit Loading (on the left) and Bit and Power Loading (on the right) strategies on a 4x8 GBaud signal.

bit loading or bit and power loading with respect to flat power. Experimental validation is performed using the same sets of constellations and power ratios obtained analytically. Then, thanks to data post-processing, it is possible to get the best constellations and power ratios for experimental results, which are reported in Table 4.3. Optimized experimental power ratios in case of power loading and bit and power loading are the same because, in case of bit and power loading, the optimal configurations are all 4x16QAM regardless the number of cascaded WSS.

As expected and demonstrated by comparing theory and simulations, experimental results are quite different from theoretical ones when 4 subcarriers are used. Also best modulation formats and power ratios are a little bit different, in particular best configurations using bit loading. Neglecting back-to-back penalty, of about 0.8 dB, experimental SNRs are higher than theoretical values: at 1 cascaded WSS, in case of flat power, the experimental required SNR is 1.5 dB higher than the theoretical one, and at 7 WSS is almost 4 dB higher. When power loading, bit loading or bit and power loading are used, this inscrease is not so high as for flat power (around 3 dB), but still not acceptable. Differently from theoretical results, for experimental results there is a gain of almost 2 dB if power loading, bit loading or bit and power loading are used instead of flat power strategy. In particular, for higher number of cascaded WSS, bit loading strategy is better than bit

N_{WSS}	Power Ratio per SC [dB] *PL strategy*				Power Ratio per SC [dB] *BPL strategy*			
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.3	-0.3	-0.3	0.3	0.3	-0.3	-0.3	0.3
2	0.4	-0.5	-0.5	0.4	0.4	-0.5	-0.5	0.4
3	0.6	-0.8	-0.8	0.6	0.6	-0.8	-0.8	0.6
4	0.8	-0.9	-0.9	0.8	0.8	-0.9	-0.9	0.8
5	0.8	-1.1	-1.1	0.8	0.8	-1.0	-1.0	0.8
6	1.0	-1.3	-1.3	1.0	-0.7	0.6	0.6	-0.7
7	1.1	-1.4	-1.4	1.1	1.1	-1.4	-1.4	1.1

Table 4.2: Optimized theoretical power ratios per sub-carrier using Power Loading (on the left) and Bit and Power Loading (on the right) strategies on a 4x8 GBaud signal.

N_{WSS}	Modulation Format per SC *BL strategy*	Modulation Format per SC *BPL strategy*	Power Ratio per SC [dB] *PL and BPL strategies*			
0	16 16 16 16	16 16 16 16	0.0	0.0	0.0	0.0
1	16 16 16 16	16 16 16 16	0.3	-0.3	-0.3	0.3
2	16 16 16 16	16 16 16 16	0.6	-0.6	-0.6	0.6
3	8 32 32 8	16 16 16 16	0.8	-1.3	-1.3	0.8
4	8 32 32 8	16 16 16 16	0.8	-0.9	-0.9	0.8
5	8 32 32 8	16 16 16 16	1.1	-1.2	-1.2	1.1
6	8 32 32 8	16 16 16 16	1.2	-1.7	-1.7	1.2
7	8 32 32 8	16 16 16 16	1.3	-2.0	-2.0	1.3

Table 4.3: Best experimental constellations using Bit Loading (on the left) and Bit and Power Loading (in the center) strategies and experimental power ratios using Power Loading and Bit and Power Loading strategies (on the right) for a 4x8 GBaud signal.

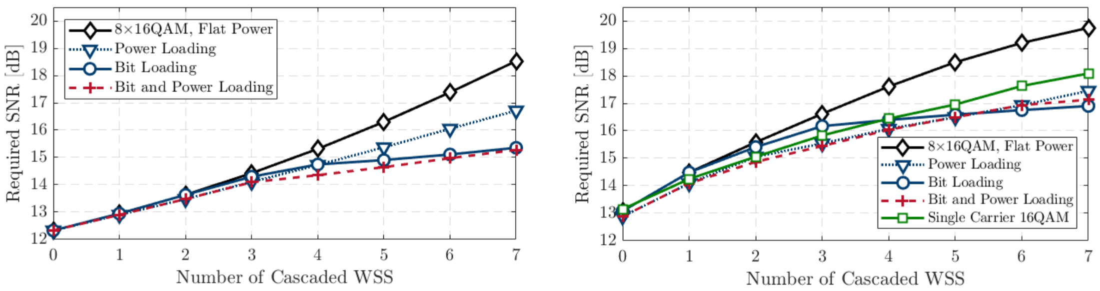
and power loading. According to previous considerations, in case of 4 subcarriers, theory cannot be used to predict the penalty due to filtering effects for an increasing number of cascaded WSS.

Moreover, required SNR obtained in case of single-carrier are always lower than 4x16QAM flat power. Up to 5 cascaded WSS, despite the use of bit loading and/or power loading strategies, single-carrier is more robust to filtering effects than a 4 multi subcarrier signal. Multiplexing over 4 subcarriers starts to pay off using bit loading strategy when 6 or more WSS are cascaded, but the gain is so small that single-carrier is more convenient.

4.2 8 subcarriers

Proceeding like in case of 4 subcarriers, still neglecting the back-to-back penalty of about 0.8 dB, it results that now the evolution of experimental SNR versus number of cascaded WSS is very similar to the theoretical trend, as depicted in Figure 4.4.

Based on theoretical results, only after 3 cascaded WSS it starts to be convenient to use power loding, bit loading and bit and power loading strategies. As expected, lower required SNRs are provided by bit and power loading strategy, whose best constellations



(a) *Theoretical results* (b) *Experimental results*

Figure 4.4: *Theoretical and experimental required SNR for an 8x4GBaud signal after WSS filtering.*

Nwss	Modulation Format per SC *BPL strategy*	Power Ratio per SC [dB] *BPL strategy*							
0	16 16 16 16 16 16 16 16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	16 16 16 16 16 16 16 16	0.7	-0.1	-0.3	-0.3	-0.3	-0.3	-0.1	0.7
2	16 16 16 16 16 16 16 16	1.1	-0.2	-0.5	-0.6	-0.6	-0.5	-0.2	1.1
3	4 16 32 32 32 32 16 4	-2.9	-0.5	1.2	1.1	1.1	1.2	-0.5	-2.9
4	4 16 32 32 32 32 16 4	-2.2	-0.5	1.0	1.0	1.0	1.0	-0.5	-2.2
5	4 16 32 32 32 32 16 4	-1.6	-0.5	0.9	0.8	0.8	0.9	-0.5	-1.6
6	4 16 32 32 32 32 16 4	-1.1	-0.5	0.7	0.6	0.6	0.7	-0.5	-1.1
7	4 16 32 32 32 32 16 4	-0.7	-0.5	0.6	0.5	0.5	0.6	-0.5	-0.7

Table 4.4: Best theoretical constellations (on the left) and optimized theoretical power ratios (on the right) using Bit and Power Loading strategy on an 8x4 GBaud signal.

and power ratios are reported in Table 4.4. After 7 cascaded WSS, the maximum gain over flat power is more than 3 dB, obtained using bit and power loading. Then it is followed by bit loading (best theoretical constellations in Table 4.5 on the left) and power loading (optimized theoretical power ratios in Table 4.5 on the right). Experiental results show that it is always convenient to use other strategies instead of flat power: up to 5 cascaded WSS, power loading and bit and power loading strategies provide lower SNR, whereas, after 5 cascaded WSS, bit loading is better. Now, at 7 cascaded WSS, the maximum gain of bit loading over flat power is almost 3 dB, less than for theory. Moreover, power loading experimental trend improves with respect to the theoretical one, maybe because of the slightly increase of pre-emphasis used to counteract bandwidth limitations. Best experimental constellations and experimental power ratios for power loading, bit loading and bit and power loading are reported in Tables 4.6, 4.7 and 4.8. Based on these considerations, theory can be used to offline predict filtering effects on system performance when few WSS are cascaded.

Comparing single-carrier and 8 multi subcarrier, it follows that the single-carrier signal is more robust to filtering effects than the 8 multi subcarrier signal with flat power. If bit and/or power loading are applied, there is a gain over single-carrier modulation, which, for 7 cascaded WSS, is between 0.5 dB and ~ 1 dB depending on the strategy. In case of bit

N_{WSS}	Modulation Format per SC *BL strategy*	Power Ratio per SC [dB] *PL strategy*							
0	16 16 16 16 16 16 16 16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	16 16 16 16 16 16 16 16	0.7	-0.1	-0.3	-0.3	-0.3	-0.3	-0.1	0.7
2	16 16 16 16 16 16 16 16	1.1	-0.2	-0.5	-0.6	-0.6	-0.5	-0.2	1.1
3	8 16 16 32 32 16 16 8	1.6	-0.4	-0.9	-0.9	-0.9	-0.9	-0.4	1.6
4	4 16 32 32 32 32 16 4	2.2	-0.6	-1.3	-1.3	-1.3	-1.3	-0.6	2.2
5	4 16 32 32 32 32 16 4	2.3	-0.6	-1.4	-1.5	-1.5	-1.4	-0.6	2.3
6	4 16 32 32 32 32 16 4	2.8	-0.8	-1.9	-2.0	-2.0	-1.9	-0.8	2.8
7	4 16 32 32 32 32 16 4	3.2	-1.1	-2.4	-2.5	-2.5	-2.4	-1.1	3.2

Table 4.5: Best theoretical constellations using Bit Loading (on the left) and optimized theoretical power ratios using Power Loading strategy (on the right) on an 8x4 GBaud signal.

N_{WSS}	Modulation Format per SC *BL strategy*	Modulation Format per SC *BPL strategy*
0	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16	16 16 16 16 16 16 16 16
2	8 16 16 32 32 16 16 8	8 16 16 32 32 16 16 8
3	4 16 32 32 32 32 16 4	8 16 16 32 32 16 16 8
4	4 16 32 32 32 32 16 4	8 16 16 32 32 16 16 8
5	4 16 32 32 32 32 16 4	16 16 16 16 16 16 16 16
6	4 16 32 32 32 32 16 4	16 16 16 16 16 16 16 16
7	4 16 32 32 32 32 16 4	4 16 32 32 32 32 16 4

Table 4.6: Best experimental constellations using Bit Loading (on the left) and Bit and Power Loading (on the right) strategies on an 8x4 GBaud signal.

loading, this gain is a little bit more than 1 dB.

4.3 16 subcarriers

When a 16x2GBaud MSC signal is transmitted, theoretically, the trends of required SNR curves are steeper than when the number of subcarrier is smaller. From Figure 4.5a best results are obtained when bit and power loading strategy is used and their theoretical best configurations and optimized power ratios are respectively reported in Tables 4.9, 4.10 and 4.11.

The use of bit and power loading starts to pay off after 2 cascaded WSS; in fact, when they are 3, the gain over the 16x16QAM flat power signal is almost 1 dB, and when they are 7, it is much more than 3 dB (around 5 dB). Similar performance is provided by bit loading strategy, which is slightly worse than bit and power loading. Power loading is worse than bit loading and bit and power loading, but still better than flat power with a 3 dB gain when 7 WSS are cascaded. Best theoretical modulation formats for bit loading and optimized theoretical power ratios for power loading are respectively reported in Tables 4.12, 4.13 and 4.14.

Analysing experimental results (Figure 4.5b), also when 16 subcarriers are use, as for

N_{WSS}	Power Ratio per SC [dB] *PL strategy*							
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.8	-0.2	-0.3	-0.4	-0.4	-0.3	-0.2	0.8
2	1.5	-0.4	-0.7	-0.8	-0.8	-0.7	-0.4	1.5
3	2.0	-0.6	-1.1	-1.2	-1.2	-1.1	-0.6	2.0
4	2.5	-0.8	-1.5	-1.6	-1.6	-1.5	-0.8	0.8
5	2.8	-0.9	-1.9	-2.0	-2.0	-1.9	-0.9	2.8
6	3.1	-1.1	-2.2	-2.3	-2.3	-2.2	-1.1	3.1
7	3.3	-1.3	-2.6	-2.7	-2.7	-2.6	-1.3	3.3

Table 4.7: Experimental power ratios per subcarrier using Power loading strategy on an 8x4 GBaud signal.

N_{WSS}	Power Ratio per SC [dB] *BPL strategy*							
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.8	-0.2	-0.3	-0.4	-0.4	-0.3	-0.2	0.8
2	-0.4	-0.5	-0.9	1.4	1.4	-0.9	-0.5	-0.4
3	0.3	-0.6	-1.2	1.1	1.1	-1.2	-0.6	0.3
4	1.0	-0.7	-1.5	0.8	0.8	-1.5	0.7	1.0
5	2.8	-0.9	-1.9	-2.0	-2.0	-1.9	-0.9	2.8
6	3.1	-1.1	-2.2	-2.3	-2.3	-2.2	-1.1	3.1
7	-0.2	-0.6	0.5	0.3	0.3	0.5	-0.6	-0.2

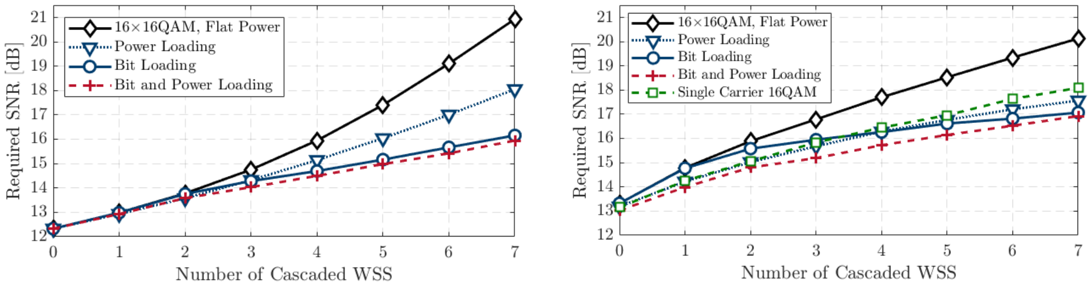
Table 4.8: Experimental power ratios per subcarrier using Bit and Power loading strategy on an 8x4 GBaud signal.

8 subcarriers, the trends of required SNR versus the number of cascaded WSS resemble theoretical trends, if optical back-to-back penalty is ignored. As expected, flat power provides worst performance, which can be improved if bit and/or power loding strategies are used. It is interesting to notice that there is a gain over flat power of almost 1 dB already in case of just one cascaded WSS and, after passing through 7 cascaded WSS, the maximum gain over flat power becomes 3 dB. Best experimental configurations and power ratios for bit loading, power loading and bit and power loading strategies are reported in Tables 4.15-4.20.

The 32 GBaud single-carrier signal is still more robust against filtering effects than the simple 16x2 GBaud signal without any bit and/or power loading. Therefore, subcarrier multiplexing is convenient only if more advanced techniques, as bit and/or power loading, are used to improve performance.

4.4 2 subcarriers

Another case that can be considered is when subcarrier multiplexing is performed on 2 subcarriers. Now the transmitted signal is a 2x16 GBaud signal and the only possible modulation format able to provide 200G capacity is 2x16QAM. Thus, it has no meaning to apply bit loading, power loading or bit and power loading strategies, since they provide the



(a) Theoretical results   *(b) Experimental results*

Figure 4.5: *Theoretical and experimental required SNR for a 16x2GBaud signal after WSS filtering.*

N_{WSS}	**Modulation Format per SC** *BPL strategy*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	8 16 16 16 16 16 16 32 32 16 16 32 32 16 16 8
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
5	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 4.9: Best theoretical constellations using Bit and Power Loading strategy on a 16x2 GBaud signal.

same results as flat power: 2x16QAM modulation format and 0.0 dB power ratio per each subcarrier regardless the number of cascaded WSS. This can be observed in Figure 4.6, where for theoretical results the four curves coincide. The same for experimental results, for which only flat power and bit loading strategies are shown. Since performance is not improved through these advanced techniques, single-carrier provides lower required SNRs when the number of cascaded WSS increases, therefore in this case there is no advantage in using subcarrier multiplexing.

4.5 Flat power versus Bit and Power Loading

Figure 4.7 summarise the results related to required SNR versus the number of subcarriers when different numbers of WSS are cascaded. As already previously observed, the more cascaded WSS are present, the higher the required SNR. When no cascaded WSS are present, the required SNR decreases when the number of subcarriers increases, also in case of flat power. Moreover, the gain of using bit and power loading over flat power is not so significative. If the number of cascaded WSS increases, the required SNR in case of flat power start to increase, whereas the required SNR obtained after bit and power loading start to decrease. Therefore, the gain of bit and power loading over flat power is higher for

N_{WSS}	Power Ratio per SC [dB] *BPL strategy*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	1.0	0.3	-0.1	-0.2	-0.3	-0.3	-0.3	-0.3
2	0.6	0.6	-0.2	-0.6	-0.7	-0.8	-0.8	1.4
3	-1.5	0.9	-0.2	-0.7	-0.9	-0.9	1.2	1.2
4	-0.7	1.1	-0.1	-0.8	-1.1	-1.1	1.0	1.0
5	0.1	-3.0	-0.2	-1.1	0.8	0.7	0.7	0.7
6	0.5	-2.5	-0.1	-1.1	0.7	0.6	0.5	0.5
7	1.3	-2.1	0.0	-1.3	0.5	0.3	0.3	0.3

Table 4.10: Optimized theoretical power ratios per subcarrier from 1 to 8 using Bit and Power loading strategy on a 16x2 GBaud signal.

N_{WSS}	Power Ratio per SC [dB] *BPL strategy*							
	9	*10*	*11*	*12*	*13*	*14*	*15*	*16*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	0.3	1.0
2	1.4	-0.8	-0.8	-0.7	-0.6	-0.2	0.6	0.6
3	1.2	1.2	-0.9	-0.9	-0.7	-0.2	0.9	-1.5
4	1.0	1.0	-1.1	-1.1	-0.8	-0.1	1.1	-0.7
5	0.7	0.7	0.7	0.8	-1.1	-0.2	-3.0	0.1
6	0.5	0.5	0.6	0.7	-1.1	-0.1	-2.5	0.5
7	0.3	0.3	0.3	0.5	-1.3	0.0	-2.1	1.3

Table 4.11: Optimized theoretical power ratios per subcarrier from 9 to 16 using Bit and Power loading strategy on a 16x2 GBaud signal.

large number of subcarriers and cascaded WSS, reaching the maximum value of 3.2 dB in case of 7 cascaded WSS and 16 subcarriers.

N_{WSS}	**Modulation Format per SC** *BL strategy*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
2	8 16 16 16 16 16 16 32 32 16 16 32 32 16 16 8
3	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
4	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
5	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 4.12: Best theoretical constellations using Bit Loading strategy on a 16x2 GBaud signal.

N_{WSS}	**Power Ratio per SC [dB]** *BPL strategy*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	1.0	0.3	-0.1	-0.2	-0.3	-0.3	-0.3	-0.3
2	1.9	0.7	-0.1	-0.5	-0.6	-0.7	-0.7	1.7
3	2.3	0.9	-0.1	-0.7	-0.9	-0.9	-1.0	-1.0
4	3.0	1.2	-0.2	-1.0	-1.3	-1.1	-1.4	-1.4
5	3.6	1.5	-0.4	-1.4	-1.7	-1.9	-1.9	-1.9
6	4.2	1.8	-0.6	-1.8	-2.2	-2.4	-2.4	-2.4
7	4.7	2.0	-0.8	-2.2	-2.8	-3.0	-3.0	-3.0

Table 4.13: Optimized theoretical power ratios per subcarrier from 1 to 8 using Bit and Power loading strategy on a 16x2 GBaud signal.

N_{WSS}	**Power Ratio per SC [dB]** *BPL strategy*							
	9	*10*	*11*	*12*	*13*	*14*	*15*	*16*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	0.3	1.0
2	1.7	-0.7	-0.7	-0.6	-0.5	-0.1	0.7	1.9
3	-1.0	-1.0	-0.9	-0.9	-0.7	-0.1	0.9	2.3
4	-1.4	-1.4	-1.1	-1.3	-1.0	-0.2	1.2	3.0
5	-1.9	-1.9	-1.9	-1.7	-1.4	-0.4	1.5	3.6
6	-2.4	-2.4	-2.4	-2.2	-1.8	-0.6	1.8	4.2
7	-3.0	-3.0	-3.0	-2.8	-2.2	-0.8	2.0	4.7

Table 4.14: Optimized theoretical power ratios per subcarrier from 9 to 16 using Bit and Power loading strategy on a 16x2 GBaud signal.

$\mathbf{N_{WSS}}$	**Modulation Format per SC** *BL strategy*
0	16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 16
1	8 16 16 16 16 16 16 32 32 16 16 32 32 16 16 8
2	4 16 16 16 16 16 32 32 32 32 16 16 16 16 16 4
3	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
4	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
5	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
6	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4
7	4 4 16 16 32 32 32 32 32 32 32 32 16 16 4 4

Table 4.15: Best experimental constellations using Bit Loading strategy on a 16x2 GBaud signal.

$\mathbf{N_{WSS}}$	**Power Ratio per SC [dB]** *BPL strategy*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	1.1	0.4	-0.1	-0.3	-0.3	-0.4	-0.4	-0.4
2	2.2	0.7	-0.2	-0.6	-0.8	-0.8	-0.8	-0.8
3	3.1	1.0	-0.3	-1.0	-1.2	-1.3	-1.3	-1.3
4	3.7	1.2	-0.5	-1.3	-1.6	-1.7	-1.8	-1.8
5	4.1	1.5	-0.6	-1.6	-2.0	-2.1	-2.2	-2.2
6	4.3	1.8	-0.6	-1.8	-2.3	-2.5	-2.5	-2.5
7	4.4	2.1	-0.6	-2.0	-2.6	-2.8	-2.8	-2.8

Table 4.16: Experimental power ratios per subcarrier from 1 to 8 using Power Loading strategy on a 16x2 GBaud signal.

$\mathbf{N_{WSS}}$	**Power Ratio per SC [dB]** *BPL strategy*							
	9	*10*	*11*	*12*	*13*	*14*	*15*	*16*
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	-0.4	-0.4	-0.4	-0.3	-0.3	-0.1	0.4	1.1
2	-0.8	-0.8	-0.8	-0.8	-0.6	-0.2	0.7	2.2
3	-1.3	-1.3	-1.3	-1.2	-1.0	-0.3	1.0	3.1
4	-1.8	-1.8	-1.7	-1.6	-1.3	-0.5	1.2	3.7
5	-2.2	-2.2	-2.1	-2.0	-1.6	-0.6	1.5	4.1
6	-2.5	-2.5	-2.5	-2.3	-1.8	-0.6	1.8	4.3
7	-2.8	-2.8	-2.8	-2.6	-2.0	-0.6	2.1	4.4

Table 4.17: Experiemental power ratios per subcarrier from 9 to 16 using Power Loading strategy on a 16x2 GBaud signal.

N_{WSS}	**Modulation Format per SC** *BPL strategy*
0	8 16 16 16 16 16 16 32 32 16 16 32 32 16 16 8
1	8 16 16 16 16 16 16 32 32 16 16 32 32 16 16 8
2	8 16 16 16 16 16 16 32 32 16 16 32 32 16 16 8
3	8 16 16 16 16 16 16 32 32 16 16 32 32 16 16 8
4	8 16 16 16 16 16 16 32 32 16 16 32 32 16 16 8
5	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
6	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4
7	4 8 16 16 16 32 32 32 32 32 32 16 16 16 8 4

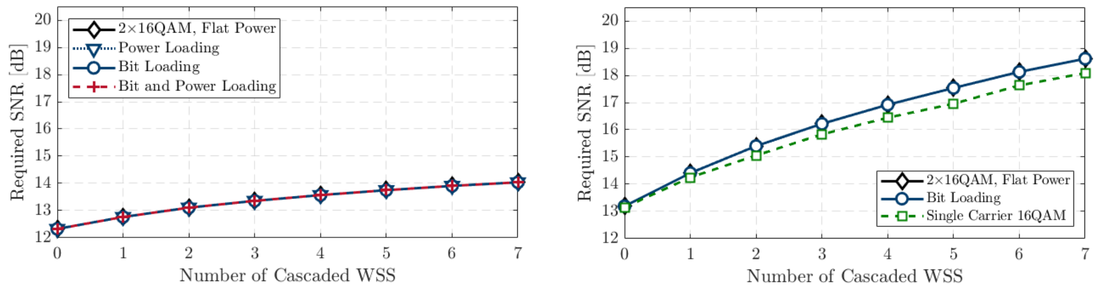
Table 4.18: Best experimental constellations using Bit and Power Loading strategy on a 16x2 GBaud signal.

N_{WSS}	**Power Ratio per SC [dB]** *BPL strategy*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
0	-1.9	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
1	-0.6	0.2	-0.2	-0.4	-0.4	-0.5	-0.5	1.7
2	0.6	0.6	-0.2	-0.6	-0.8	-0.8	-0.8	1.4
3	1.7	0.9	-0.3	-0.9	-1.1	-1.2	-1.2	1.0
4	2.6	1.1	-0.4	-1.2	-1.5	-1.6	-1.6	0.6
5	0.6	0.2	-0.2	-1.2	-1.6	0.6	0.6	0.6
6	1.3	0.6	-0.2	-1.4	-1.9	0.3	0.3	0.3
7	1.8	1.0	-0.2	-1.6	-2.2	0.0	0.0	0.0

Table 4.19: Experimental power ratios per subcarrier from 1 to 8 using Bit and Power Loading strategy on a 16x2 GBaud signal.

N_{WSS}	**Power Ratio per SC [dB]** *BPL strategy*							
	9	*10*	*11*	*12*	*13*	*14*	*15*	*16*
0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-1.9
1	1.7	-0.5	-0.5	-0.4	-0.4	-0.2	0.2	-0.6
2	1.4	-0.8	-0.8	-0.8	-0.6	-0.2	0.6	0.6
3	1.0	-1.2	-1.2	-1.1	-0.9	-0.3	0.9	1.7
4	0.6	-1.6	-1.6	-1.5	-1.2	-0.4	1.1	2.6
5	0.6	0.6	0.6	-1.6	-1.2	-0.2	0.2	0.6
6	0.3	0.3	0.3	-1.9	-1.4	-0.2	0.6	1.3
7	0.0	0.0	0.0	-2.2	-1.6	-0.2	1.0	1.8

Table 4.20: Experimental power ratios per subcarrier from 9 to 16 using Bit and Power loading strategy on a 16x2 GBaud signal.



(a) *Theoretical results*

(b) *Experimental results*

Figure 4.6: *Theoretical and experimental required SNR for a 2x16GBaud signal after WSS filtering.*

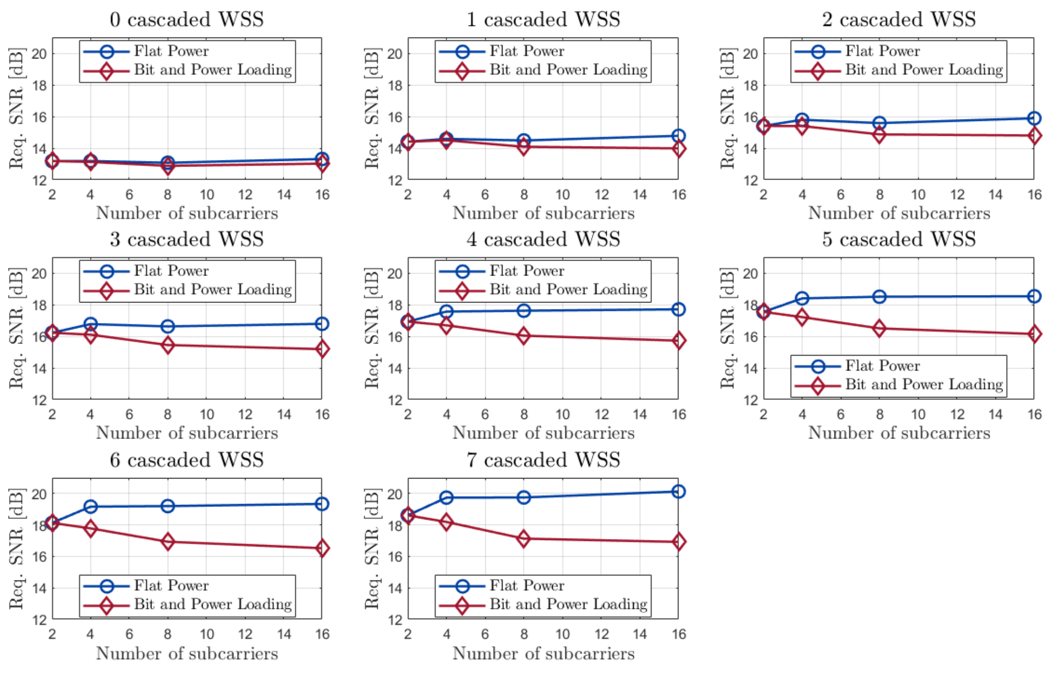


Figure 4.7: *Experimental required SNR in case of Flat Power and Bit and Power Loading strategies for increasing number of subcarriers and cascaded WSS.*

Chapter 5

Conclusions

The purpose of this thesis is to provide a valid solution to reduce filtering effects due to the presence of several cascaded ROADMs. The system studied is a 200G system, for which nowadays the most common form of modulation is a single-carrier 32 GBaud PM-16QAM signal. The supported and developed solution proposes the use of subcarrier multiplexing and advanced bit and/or power loading strategies to mitigate filtering effects due to an increasing number of cascaded WSS, in this thesis up to 7. To find the best solution, different number of subcarriers have been studied. When the number of cascaded WSS increases, system performance improves if bit and/or power loading strategies are applied, in particular bit and power loading, which provides the best results. Moreover, when these advanced strategies are used, SD-FEC technique results to be better than HD-FEC, since, in same conditions (same number of subcarriers and same number of cascaded WSS), the required SNRs are lower.

Simulation results show that theory cannot be used for a fast offline evaluation of the required SNR when the number of subcarriers is lower than 8. In fact, when 4 subcarriers are simulated using theoretical power ratios, system performance in case of actual WSS filtering are very bad even when equalization is performed and bit and power loading strategy is applied. To get better results bit and power loading based on optimized power ratios should be performed, which unfortunately is time consuming. Another proof supporting the fact that theory is not valid for a 4x8 GBaud SCM signal can be observed by comparing theoretical and experimental results. From theoretical results, it seems that the system is robust to filtering effects even for larger numbers of cascaded WSS and flat power, since the penalty passing through 7 cascaded WSS is less than 3 dB. Furthermore, it also seems that there is not a big gain in using bit and/or power loading strategies. On the contrary and according to simulations, experiments show that the increase of the required SNR is higher than the one expected from theory and that the gain in using bit and/or power loading over flat power is around 2 dB. Besides these improvements, there is no gain in using 4 subcarriers instead of single-carrier.

Similar observations can be made in case of 2 subcarriers, for which the difference between theoretical and experimental results is even more significative.

When an 8x4 GBaud SCM signal is transmitted (8 subcarriers are used), simulations prove that results obtained with actual WSS filtering and equalization are similar to those obtained using the approximated WSS filtering, i.e. they are similar to theory simulation.

In particular, best performance are given when bit loading and bit and power loading strategies are used. Performing power ratio optimization for bit and power loading in case of actual WSS filtering, the required SNRs obtained using theoretical power ratios and the required SNRs obtained using optimized power ratios are almost the same, even without equalization. This result is valid for both noise lumped at the receiver scenario and equally distributed noise scenario and is important in case of equally distributed noise because theoretical power ratios are analytically computed for the lumped noise at the receiver scenario. Thus, theory can be used for a quick evaluation of system performance in case of an 8x4 GBaud SCM signal. Simulation results are validated experimentally, for which the actual gain of using bit and/or power loading over flat power is around 3 dB when 7 WSS are cascaded. Moreover, there is a gain also over single-carrier, whose maximum value, crossing 7 cascaded WSS, is 1 dB when bit loading is used.

Simulating 16 subcarriers, results show that, when bit loading and bit and power loading strategies are used with theoretical power ratios, required SNR trend obtained in case of actual WSS filtering without equalization is the same as the one obtained in case of approximated WSS filtering without equalization. Performing bit and power loading optimization, bit and power loading trend based on theoretical power ratios coincides with bit and power loading trend based on optimized power ratios. This means that, theoretical power ratios are enough to evaluate system performance. Thus, for bit loading and bit and power loading strategies, theory can be used to quickly evaluate the required SNR for an increasing number of cascaded WSS and to understand if there is a gain over single-carrier. As for the 8x4 GBaud SMC signal, these considerations are significative because they are valid for both lumped noise at the receiver and equally distributed noise scenarios. Instead, for power loading strategy based on theoretical power ratios, required SNR curve obtained for actual WSS filtering follows the curve obtained in case of approximated WSS filtering only if equalization is applied. Looking at theoretical and experimental results, if optical back-to-back penalty is neglected, theoretical flat power provides higher required SNR values than those provided by experiments. The same in case of power loading. Therefore, if theory is used to evaluate the required SNR for an increasing number of cascaded WSS, it would provide a worse estimation than the actual one. This is no longer true when bit loading and bit and power loading strategies are used. In fact, neglecting optical back-to-back penalty, theoretical and experimental system performance are similar in terms of required SNR. From experimental results, with 7 cascaded WSS, the use of bit and power loading allows to gain 3 dB over flat power and 1 dB over single-carrier.

Excluding 2 and 4 subcarriers, which do not provide significative gains over single-carrier, from an experimental point of view, system performance are very similar when 8 and 16 subcarriers are used. In particular in case of bit and power loading strategy in terms of required SNR and gain over single-carrier. The only difference among the two is in complexity, which is higher in case of 16 subcarriers. Therefore, 8 subcarriers are preferable than 16 subcarriers and best performance are obtained when bit and power loading strategy is used.

This work could be further extended introducing an optical recirculating loop, which emulates long distance links. In this case, because of the presence of a real optical fiber link, non-linear effects occur, contributing to system performance degradation. Therefore, they have to be taken into account during system analysis.

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