REAL-time monitoring and mitigation of nonlinear effects in optical **NET**works (REAL-NET)

D3.1 Real-time optical performance monitoring for meshed optical networks using EON architecture

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Contents

ACRONYMS

BER	Bit Error Rate
BVT	Bandwidth Variable Transponders
DC	Data Center
DSCM	Digital SubCarrier Multiplexing
DSP	Digital Signal Processing
EON	Elastic Optical Networks
FEC	Forward Error Correction
MF	Modulation Format
OA	Optical Amplifier
OSNR	Optical Signal-to-Noise Ratio
QAM	Quadrature Amplitude Modulation
QoT	Quality of Transmission
QPSK	Quadrature Phase Shift Keying
ROADM	Reconfigurable Optical Add/Drop Multiplexers
Rx	Receiver
SC	SubCarrier
SDN	Software Defined Networking
SE	Spectral Efficiency
SR	Symbol Rate
Tx	Transmitter
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switches

1 DESCRIPTION OF THE DELIVERABLE

Hybrid filterless and filtered metro transport networks, together with autonomous digital subcarrier multiplexing systems based on elastic optical networks are introduced and described. The most important parameters to be monitored in these future optical systems are identified.

2 REPORT

2.1 Introduction

The global exponential increase of the data traffic shows no signs of slowing down. With the recent developments on 5G and beyond technologies, cloud services, high-speed access networks, etc. is expected an even faster and higher increase of IP data traffic generation. Furthermore, current data traffic is heterogeneously generated in terms of Modulation Format (MF), Symbol Rate (SR), and also originated from different sources. In this way, the optical transport networks, which are responsible to transport all data traffic around the world, need to be designed and monitored in a cost-effective and efficient way to face these continuous increments.

One of the technologies that enabled the overall improvement of the Spectral Efficiency (SE) in optical transport networks, i.e., the efficient use of the frequencies available to transmit the signals, is the Elastic Optical Networks (EON) technology. In these kinds of networks, the data traffic can be assigned in different spectral widths (or optical channels). In order to improve even more the performance of these networks, the monitoring of the several parameters involved in these network environments is a key feature. In this report, we firstly focus our investigations on the performance of high order MF with fast SR in EONs. Second, we study the achievable improvements with the use of a new promise technology, the Digital Subcarrier Multiplexing (DSCM). In this report, our main focus is on clarifying which are the most important parameters to be monitored in future optical systems based on EONs and DSCMs systems.

2.2 High-order modulation formats and fast symbol rates

The availability of Wavelength Selective Switches (WSS), together with the support of Bandwidth Variable Transponders (BVT) [1] operating at SRs beyond 32 GBd [2]-[4] and high-order MF based on Quadrature Amplitude Modulation (QAM) formats, have enabled the deployment of EONs [5]. EONs development, as stated, led to an overall increase of SE and allowed to extend the optical transmission technologies towards the network edge [6]. Next generation of BVTs might be soon capable to generating and transmitting SRs as faster as 96 GBd with MF employing 64QAM together with probabilistic shaping and digital subcarrier multiplexing systems [7]. Based on currently commercially available WSSs, the flexible grid concept is possible, and a frequency granularity of 6.25 GHz and tighter can be considered thus, leading to several options for different optical channels.

Some studies about the impact of optical filtering on high-order MFs and faster SRs can be found in the literature. For example, the authors in [3],[4] studied the impact of optical filtering assuming 75 and 100 GHz channel spacing on signals that pass through several Reconfigurable Optical Add/Drop Multiplexers (ROADM), on typical Wavelength Division Multiplexing (WDM) core networks. Owing to the fact of physical layer impairments, such as optical filtering, lower order MFs must be used in these scenarios.

In this section, we focus in the application of high order MFs in hybrid filterless and filtered metro networks; specifically, we investigate the optical filtering impact considering 32, 64 and 96 GBd, 32 and 64 QAM, and channels spacing from 37.5 to 150 GHz. The objective is to avoid high Optical Signal-to-Noise Ratio (OSNR) penalties due to the optical filtering, while maximizing the SE of the resulting systems.

Although, WSSs inside of ROADMs play an important role to transparently route an optical signal along its lightpath, they impair network performance due to filter cascading effects (bandwidth narrowing entails OSNR penalties), as well as being a point of failure that causes Quality of Transmission (QoT) degradation [8]. The narrow filtering occurs because of the non-ideal transfer function of the WSSs, which results to be narrower than the nominal selected value [9]. Further degradation can be caused by the frequency shift between WSSs and the channel.

One important feature for 5G and beyond transport networks, alongside with higher capacities, is that of low latency for connectivity services between the access and the services running in metro and core Data Centers (DC). In that regard, filterless segments (e.g., in the form of horseshoes/bus topologies) can be used to extend the filtered metro core network to reach the access one [10]. Fig. 1 represents one targeted scenario with the filtered metro mesh topology implemented with ROADMs and a filterless edge horseshoe topology with filterless nodes based on optical splitters/couplers (and optical amplifiers if needed). The internal architecture of each node is shown in the inner figure. Besides, let us assume that metro/core DCs can be collocated with the ROADMs.

We are interested in studying the QoT experienced by signals connecting a node in the horseshoe, typically an aggregation node connecting one or more access networks (including radio and fixed access), and a metro/core DC collocated with one of the ROADMs. Therefore, in the case that a metro/core DC is collocated to one of the end ROADMs in the local horseshoe (ROADM-1A/B in Fig. 1), a lightpath connecting a filterless node (R1..4 in Fig. 1) to that DC1 would only traverse one single ROADM, i.e., two WSSs. However, since not all metro nodes could be equipped with computation capabilities, the lightpath might traverse additional ROADMs in their path, e.g., to DC2, or even to DC10.

To evaluate the system performance for high-order MF and fast SR, we are performing Monte-Carlo numerical simulations. At the transmitter side, we generated 2^{13} pseudo-random binary sequences shaped by a root-raise cosine filter with 0.15 roll-off factor and consider the aforementioned SRs and MFs. The impact of optical filtering is studied on two different lightpaths/scenarios that corresponds to the cases where the DC is collocated with the ROADM in the local horseshoe or with a different metro core ROADM (denoted as Scenario 1 and 10) as a function of the number of ROADMs that the signal traverses, i.e., Scenario 1 is, for example, lightpath R2-DC1 and Scenario 10: R2-DC10, where the signal crosses 10 ROADMs. The two scenarios are represented in Fig. 1 by the orange line. Note that, to model the ROADMs, we assume that they are based on a route-and-select architecture, i.e. WSSs at ingress/egress stages, add/drop structures based on WSSs and pre and booster Optical Amplifiers (OA).

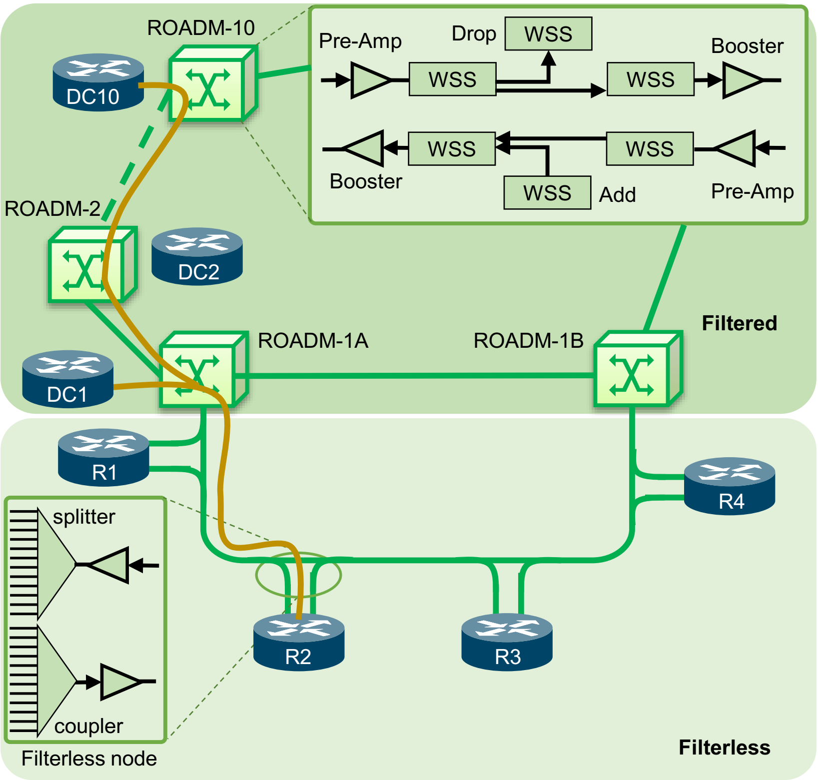

Fig. 1. Hybrid filterless and filtered-based metro network.

To model the spectral shape of the WSSs, we averaged out real spectral measurements from 4 different optical channels for each channel spacing considered [9]. Fig. 2 represents an example of the passband filters transfer function for the 50, 87.5 and 112.5 GHz channels; the -3 dB bandwidth obtained for these filters is about 46.3, 83.6 and 110.2 GHz, respectively. Note that, as the filter transfer functions were evaluated by real spectral measures, they also include filter ripples, which will accumulate with the cascaded filters [9].

Regarding the optical amplification, all OAs are modeled as erbium doped fiber amplifiers working in the C-band. We assume a pre-amplifier gain to compensate the losses from the previous span and a booster gain to compensate exactly the insertion losses of the WSSs (of about 4.4 dB as shown in Fig. 2); both OAs with noise figure of 6 dB. In this report, we consider a filterless segment (metro edge) with about 40 km, a filtered (metro/core segment) with 100 km, both with fiber attenuation factor of 0.25 dB/km. The amplified spontaneous emission noise power generated by the OAs is obtained by the spectral information in a 12.5 GHz (0.1 nm) reference bandwidth.

Finally, we assume an ideal optical coherent receiver and direct error counting to estimate the Bit Error Rate (BER), considering a total of 1000 errors and with target pre-Forward Error Correction (FEC) of 4×10^{-3}, one order of magnitude lower than the selected pre-FEC threshold in order to guarantee enough system margin.

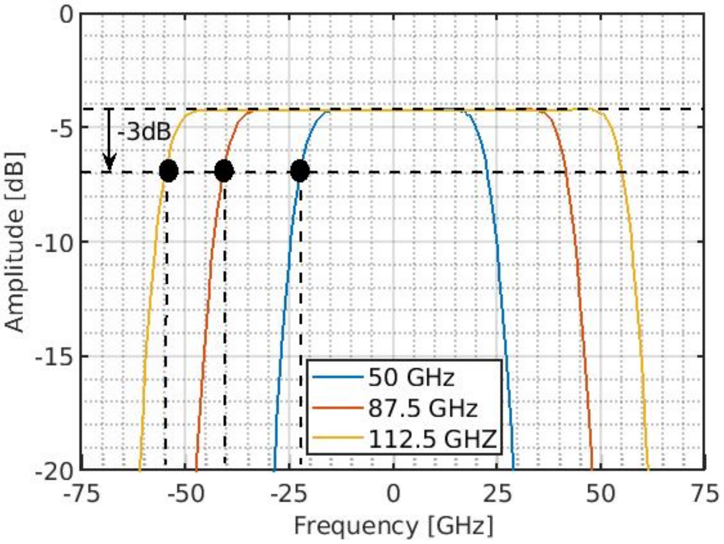

Fig. 2. WSS transfer functions for 50, 87.5 and 112.5 GHz optical channel spacing.

2.3 Digital subcarrier multiplexing systems

DSCM systems together with advanced Digital Signal Processing (DSP) modules represent one of the key technologies to route transparently heterogenous data in an efficient and cost-effective way [11],[12]. The key aspect of DSCM is the usage of multiple digital subcarriers (SC), e.g., 4, 8 or more. One of the main benefits of using DSCM in optical transport networks is to keep high capacities while using lower SRs per SC, which leads to lower penalties caused by fiber propagation impairments, such as dispersion and nonlinear Kerr effects [12],[13]. The DSCM is realized at the Transmitter (Tx) side and each SC is individually detected and post-processed at the coherent Receiver (Rx); thus, different SCs with different MF and SR might coexist. The flexibility enabled by DSCM can be exploited to dynamically adapt the capacity of optical connections to the real amount of traffic that are actually supporting, thus reducing energy consumption. In fact, of the total power consumption of a coherent optical transponder, more than 87% is required from subsystems that could be switched off in case a SC is de-activated [14]. To that end, the Software Defined Network (SDN) controller can be in charge of configuring each of the SCs of every optical connection by programming both Tx and Rx transponders with the specific configuration. However, this would significantly increase the number of tasks to be performed in within the controller, as well as to add complexity because of near real-time decision making.

In this section, we propose a decentralized approach where the Tx makes the SC configuration decisions autonomously and the Rx is able to recognize such configuration. In addition, both Tx and Rx can send notifications of SC-related events to the SDN controller, so it can be aware of the current configuration. We propose delegating to the transponders the autonomous operation of an optical connection. Once the optical connection is established by the SDN controller, the Tx autonomously decides the right configuration of the SCs to allocate sufficient capacity in the optical connection for the incoming traffic, whereas the Rx automatically detects the active SCs and configures its MF and SR.

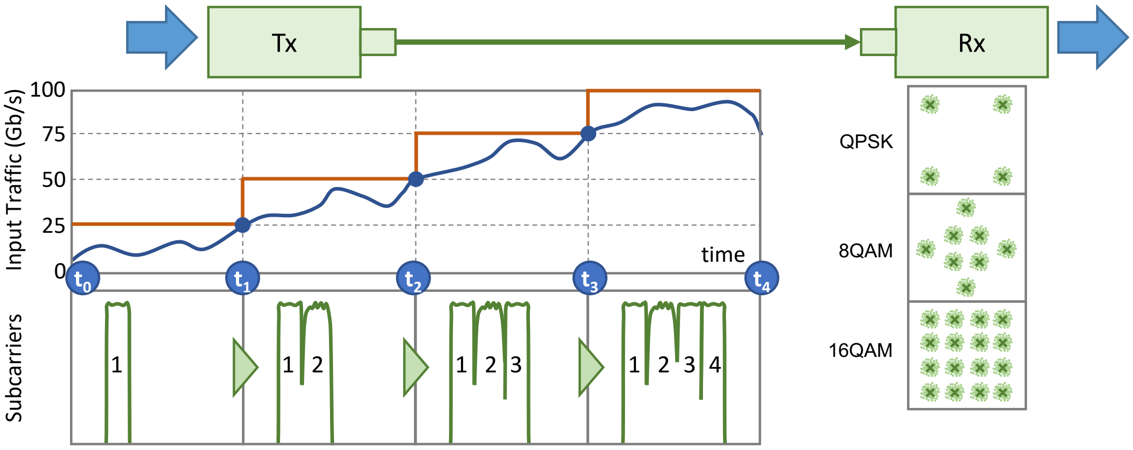

Fig. 3. Autonomous SC configuration.

Fig. 3 presents an example of evolution of the input traffic over time and the active configuration, as decided by the Tx. At time t_0, the connection is set up by the SDN controller that allocates the needed spectrum width along the path connecting the transponders and configures one 8 GBd QPSK SC (SC1), so the capacity of the connection is about 25 Gb/s. From that moment, the SDN controller delegates the management of the capacity of the optical connection to the end transponders; the Tx can observe the amount of input traffic and make decisions in consequence. In the example in Fig. 3, based on the input traffic, the Tx decided to configure a second 8 GBd QPSK SC (SC2) at t_1 to increase the capacity of the connection to 50 Gb/s. The same decisions are made at times t_2 and t_3, until reaching a capacity of 100 Gb/s by configuring all SCs as 8 GBd QPSK signals. If the input traffic decreases (as in t_4), one or more SCs can be de-activated, thus saving energy. However, if the traffic continues increasing one of the SCs needs to be reconfigured, e.g., to an 8 GBd 16QAM signal, which would increment the capacity of the connection at the cost of a temporal decrement, which turns out into disruption and packet losses.

Such a decision-making process requires intelligence to maximize the potential capacity of the transponders without traffic disruption, while saving as much energy as possible. For instance, in view of the evolution of the traffic at t_2, the Tx could have configured SC3 as a 11 GBd 16QAM signal and then, de-activate SC2, thus resulting in the same total capacity but using two SCs instead of three.

A different analysis that has to be considered in the decision-making process, is related to the specific configuration of the optical connection, which includes, at least:

- the amount of filtering effects, which impact the *external* SCs and can limit the MF order for themes;
- the expected OSNR at the Rx. With such information, computed at set-up time, the Tx can create a map with the per-SC possible configurations.

The proposed procedure for the Tx to select the configuration of the optical connection, including which SCs need to be active and their MFs and SRs, as well as that for the Rx to recognize such configuration, is present now.

The algorithm for the autonomous management of the optical connection is presented in Table 1. The algorithm receives as input the state of the connection in terms of the configuration of the SCs, the map of feasible configurations for each SC, and the target capacity for the connection; it returns the target configuration of the connection. We assume that the target capacity is computed based on prediction, e.g., by computing the trend of the measured input traffic to allow some anticipation. In case of reduced capacity, a target SC is identified, so the total capacity of the connection still supports the requested one (lines 1-4 in Table 1). In case that an increment of capacity is requested, the proposed algorithm identifies the active SC with the largest potential capacity increase (line 5), so we can activate another SC that can support the requested capacity plus the identified active SC, which can be eventually de-activated. In the case that any active SC is identified, a non-active SC needs to be activated, which is configured to support the requested capacity if more than one SC is available, or to its maximum capacity (lines 6-10). If one active SC is identified, a non-active SC is selected to support the incremental capacity or just the requested capacity (lines 11-16).

The Rx is in charge of detecting the presence or absence of SCs and of configuring properly the ones to be activated. Such recognition can be based on the received constellation [15], and it requires to work for any optical OSNR in a given range. For instance, the method proposed in [16] requires OSNR > 20 dB and it does not consider variable SR. The approach proposed in this report relies on matching the received constellation with a MF, which is characterized by a given set of *constellation points*. The distance between the received constellation and the expected constellation points can be computed as the averaged summation of the minimum squared Euclidean distances; this is similar to a traditional clustering problem, albeit in this case the *centroids* are predefined by the constellation points of the selected MF. To find the right SC configuration, such computation is performed for all possible configurations for a given SC, and the one that minimizes the distance is selected.

Table 2 presents the pseudocode for the SC configuration recognition at the Rx side; given SC *sc* and a list of possible configurations for that SC, it returns the most likely configuration. After the initialization (lines 1-2 in Table 2), the signal is decoded and the list of possible SRs is obtained from the configuration list (line 3). Then, for each possible symbol rate *SR*, the signal is processed, and the observed constellation of symbols in the complex space is obtained (lines 4-5). Using that processed constellation, the MF that minimizes the distance is selected from the list of possible MFs for the selected SR (line 6). Finally, if the distance is smaller than the minimum obtained so far, the configuration is stored (lines 7-8).

Table 1. Connection Configuration Management at the Tx

Input: *conn, configMap, targetCapacity*

Output: *conn*

```
incCap ← targetCapacity - conn.capacity
if incCap < 0 then
    sc ← findActiveSCToTearDown (conn, -incCap)
    return <sc, ∅>
activeSC ← findMaxUpgrad (conn, configMap)
if activeSC = ∅ then
    <num, sc, config>←findNonActiveSC(conn,
                            configMap, incCap)
    if num > 1 then return <sc, config>
    if num = 1 then return <sc, getMaxConfig (configMap(sc))>
    return <∅, ∅>
<num, sc, config> ← findNonActiveSC (conn, configMap,
                            incCap + activeSC.capacity)
if num > 0 then return <sc, config>
<num, sc, config> ← findNonActiveSC (conn, configMap, incCap)
if num > 1 then return <sc, config>
if num = 1 then return <sc, getMaxConfig(configMap(sc))>
return getMaxConfigNonActive (conn, configMap)
```

Table 2. Configuration Recognition Algorithm at the Rx

Input: *sc, configList*

Output: *foundConfig*

```
foundConfig ← <MF = ∅, SR = ∅>
minDistance ← ∞
SRList = getSRList(configList)
for each SR in SRList do
    constellation←getConstellation (sc, SR)
    <MF, d> ← findFittestModFormat(constellation,
                            getMFList(configList), SR)
    if d<minDistance then
        foundConfig ← <MF, SR>; minDistance ← d
return foundConfig
```

2.4 Conclusions

The hybrid filterless and filtered metro transport networks based on higher MF and faster SR, as well as the transceivers autonomous operation in DSCM systems to save power consumption were introduced and their main features were explained.

Table 3 summarizes the parameters to be monitored in the scenarios investigated, as well as their importance. Regarding optical filtering impact on higher MF and faster SR, the implication of filters-related failures, such as filter shifts, as well as the laser drifts, both must be monitored. Concerning the autonomous DSCM systems, to manage the number of needed SCs in a given time, measurements of the historical evolution of the data traffic must be available and also the monitoring of the per-SC OSNR, BER and central frequency.

Table 3. Parameters to be monitored and their importance in both scenarios investigated

Scenarios investigated	**Parameters to monitoring**	**Importance of monitored parameters**
Optical filtering impact on higher MF and faster SR	Filter and laser frequency alignment; filter ripple	Filters and laser dealignments can lead to higher filtering penalties; filter ripples are harmful on cascaded filters
DSCM systems	Traffic evolution; OSNR, BER, central frequency per-SC	To adapt the DSCM systems for the actual needs; a per-SC monitoring will give us a better view of the system performance

Finally, we are currently working on the outcomes and planning to submit as contributions to the European Conference on Optical Communication (ECOC) 2020.

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