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

D4.1 Analysis of QoT and methods to anticipate service degradation

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Contents

ACRONYMS

ASE	Amplified Spontaneous Noise
B2B	Back-to-Back
BER	Bit Error Rate
DC	Data Center
DSCM	Digital SubCarrier Multiplexing
FEC	Forward Error Correction
GSNR	Generalized Signal-to-Noise Ratio
MF	Modulation Format
ML	Machine Learning
NLI	Nonlinear Interference
OA	Optical Amplifier
OLS	Optical Line System
OSNR	Optical Signal-to-Noise Ratio
QAM	Quadrature Amplitude Modulation
QoT	Quality of Transmission
QPSK	Quadrature Phase Shift Key
ROADM	Reconfigurable Optical Add/Drop Multiplexer
SC	SubCarrier
SR	Symbol Rate
WSS	Wavelength Selective Switches

1 DESCRIPTION OF THE DELIVERABLE

In this report, Quality of Transmission (QoT) analysis and methods to anticipate service degradation are analyzed. In particular, the service degradation due to the optical filtering on future metro transport optical networks, based on high-order Modulation Formats (MF) and fast Symbol Rates (SR), is presented and discussed. Also, the autonomous operation of the Digital Subcarrier Multiplexing (DSCM) systems to be make possible a per-SubCarrier (SC) QoT estimation is introduced and some simulation results are presented.

2 REPORT

2.1 Introduction

In this digital era, where high capacity and low latency services are key factors, a really important aspect is anticipating service degradation. As soon it is detected as fast the network operators can react in order to avoid hard network failures. One of the main approaches to detect the service degradation is a continuous and, if possible, a real-time QoT estimation. Metrics like the Optical Signal-to-Noise Ratio (OSNR) and Bit Error Rate (BER) can be monitoring and stored, for example, to apply Machine Learning (ML) algorithms to make estimations and predict future service degradation.

Nowadays, heterogenous optical signals are transparently routed along its lightpath. To make it possible, the signal crosses multiple optical nodes and, inside these nodes, it suffers optical filtering by the Wavelength Selective Switches (WSS). The optical filtering is a physical layer impairment which can induce OSNR penalties and consequently decrease the QoT. Additionally, the frequency dealignment between the filters and the signals can also leads to penalties even higher. In the next subsection, we will investigate the filtering degradation on a scenario of metro transport networks based on high-order MFs and fast SRs.

One fresh technology to improve the optical transmission is the DSCM, that enable to multiplex the data into multiple SCs instead of a single carrier. The multiple SCs can have different modulation formats and symbol rates and, consequently, the physical layer impairments can differ SC by SC. For example, the optical filtering will degrade more the external SC than the internal ones. In this way, in a DSCM scenario, a per-SC QoT estimation is important for a most accurate and understandable system performance. In subsection 2.3, we introduce and discuss the per-SC QoT estimation.

2.2 Filtering degradation on high-order modulation formats and fast symbol rates

In this subsection, we focus in the application of high order MFs in hybrid filterless and filtered metro networks; specifically, we investigate the optical filtering impact considering SRs of 32, 64 and 96 GBd, MFs of 32 and 64 QAM, and channels spacing from 37.5 to 150 GHz. The objective is to avoid high 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 QoT degradation [1]. The narrow filtering occurs because of the non-ideal transfer function of the WSSs, which results to be narrower than the nominal selected value [2].

We are interested in studying the QoT experienced by signals connecting an edge node, typically an aggregation node connecting one or more access networks (including radio and fixed access), and a metro/core Data Center (DC) collocated with one of the Reconfigurable Optical Add/Drop Multiplexers (ROADM). 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 performed 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 considering 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).

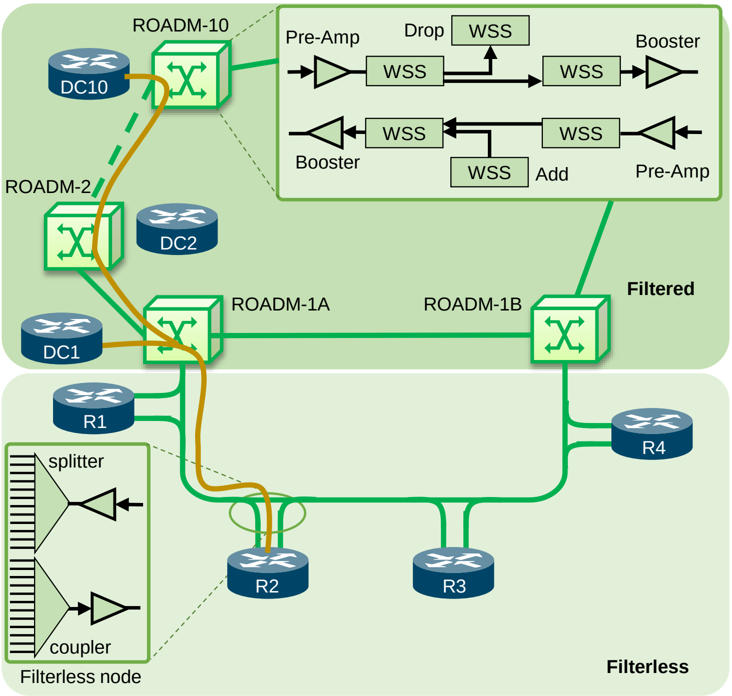


Fig. 1. Hybrid filterless and filtered-based metro network.

To model the spectral shape of the WSSs, we averaged out real spectral measurements from 4 different optical channels for each channel spacing considered [2]. 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 [2]. On the other hand, we assume a perfect alignment between the signal and the optical filters.

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 **Error! Reference source not found.**); 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.

We analyze the OSNR penalty due to optical filtering for different channels spacing and for the 2 scenarios presented in the previous section. To analyze such impact, we considered 37.5 and 50 GHz channel spacing to transmit 32 GBd signals, 75 and 87.5 GHz to transmit 64 GBd ones, and 100 and 112.5 GHz for 96 GBd signals.

Table 1 summarizes the OSNR penalties due to optical filtering obtained for all cases studied. As expected, the optical filtering has higher impact for higher order MFs, comparing the OSNR penalties for the 32QAM to those for 64QAM. Regarding channel spacing, the two tighter ones for 32 and 96 GBd signals (37.5 and 100 GHz) impose large penalties even for the best of the analyzed scenarios (cells with dash). For 64 GBd signals in the tighter channels (75 GHz), we obtained lower filtering penalties for Scenario 1, which is lower than 1 dB. However, channel spacing of 50 GHz for 32 GBd signals, 87.5 GHz for 64 GBd signals and 125 GHz for 96 GBd signals reduce optical filtering penalties to just less than 0.05 dB for almost all investigated scenarios, i.e., practically negligible filtering penalties. The only scenarios where we observed optical filtering penalties was for 64QAM 32/96GBd signals in 50/112.5 GHz after 10 ROADMs, with penalties about 1 and 0.3 dB, respectively. Assuming the above channel spacings, Fig. 2 depicts the BER as a function of the OSNR for the two scenarios, as well as for the back-to-back (B2B) one, which does not suffer from optical filtering impairments. Fig. 2(a) plots the results for 32 GBd signals in a 50 GHz optical channel, Fig. 2(b) for 64 GBd in an 87.5 GHz, and Fig. 2(c) for 96 GBd in a 112.5 GHz, in all for both 32 and 64QAM MFs. The required OSNR obtained for the threshold BER of 4×10^{-3} in the B2B scenario are about 22 dB and 26.5 dB for 32 GBd signals, 25.5 dB and 29.5 dB for 64 GBd, and 26.7 dB and 31 dB for 96 GBd for 32QAM and 64QAM, respectively.

Table 2 summarizes the SE as a function of the MF, SR and channel spacing obtained for all cases studied, considering a FEC overhead of 20% and 25% for 32 and 64QAM, respectively [3]. We observe that the SE increases as expected when increasing of the MF and SR, achieving the better one for 96 GBd, where the use of 112.5 GHz optical channels results in SE of about 6.83 and 7.68 b/s/Hz for 32 and 64QAM, respectively.

Table 1. OSNR penalties due to optical filtering for a threshold BER = 4×10^{-3}.

	32QAM		64QAM	
Ch. Spacing [GHz]	**Scenario (# of ROADMs)**			
	1	10	1	10
	32 GBd			
37.5	5.0	-	-	-
50	0	0	0	1.0
	64 GBd			
75	0.7	-	0.8	-
87.5	0	0	0	0
	96 GBd			
100	4.0	-	-	-
112.5	0	0	0	0.3

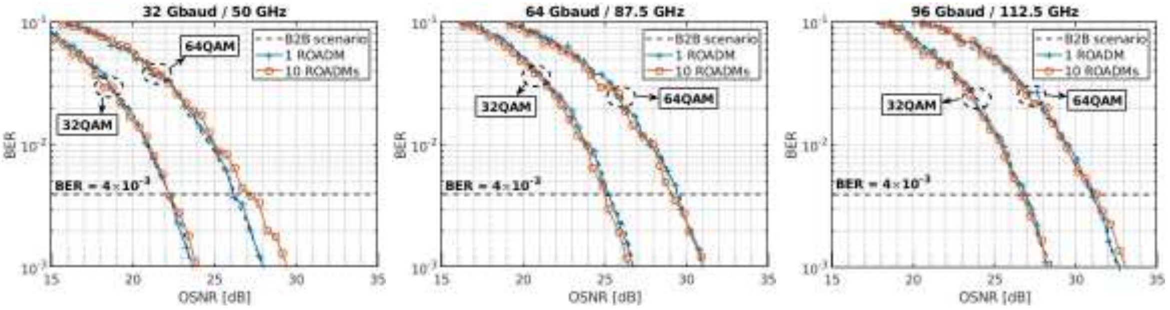


Fig. 2. BER vs OSNR for 32 GBd signals in 50 GHz channel spacing (a), 64 GBd in 87.5 GHz (b) and 96 GBd in 112.5 GHz (c).

Table 2. SE as a function of the MF, SR and channel spacing.

MF	SR [GBd]	Ch. [GHz]	Bit rate [Gb/s]	Net bit rate [Gb/s]	SE [b/s/Hz]
32QAM	32	50	320	256	5.12
	64	87.5	640	512	5.85
	96	112.5	960	768	6.83
64QAM	32	50	384	288	5.76
	64	87.5	768	576	6.58
	96	112.5	1152	864	7.68

2.3 Estimation of the QoT on digital subcarrier multiplexing systems

In this subsection, we study the performance of different SC configurations and the QoT estimation, with the aim of finding the operational limits of DSCM for autonomous capacity management. Next, the results of the SC configuration recognition algorithms, introduced on the public Deliverable 3.1 [4], is presented.

Let us first study the minimum OSNR for each configuration defined by the pair <*MF*, *SR*> assuming a back-to-back scenario; we have considered QPSK, 8QAM and 16QAM, and 8 and 11 Gbd per SC. The results have been obtained through Monte-Carlo simulation carried out in MATLAB, where a 2^{13} pseudo-random binary sequence was generated and shaped by a root-raise cosine filter with 0.15 roll-off factor, no NLI was considered. Fig. 3 presents the obtained BER, computed through direct error counting, as a function of the OSNR. Assuming a pre-FEC BER threshold of 4×10^{-3}, which includes one order of magnitude to cope with system margins, the minimum OSNR for every combination is also highlighted.

Let us now study the QoT of an optical system with 4 SCs that is conveyed over of a 100 km lightpaths, which route includes a number of ROADMs and OLSs. ROADMs consist of one WSS for add/drop and one WSS per degree and direction, which results into the optical signal crossing 2 WSSs per ROADM. In line with [2], in this study we compute an approximate value of the $FP_{n:s}(b, SR)$ that does not depend on the MF for the number of ROADM nodes considered; it is computed as the quotient between the area of the inverse of the filtering transfer function of the WSS normalized to the maximum value, and the area the SC power spectral density. For this analysis, we consider slot widths of 37.5, 50, and 62.5 GHz. OLSs include OAs with a noise figure equal to 5 dB and ITU-T G.652.D fibers with attenuation equal to 0.2 dB/km, dispersion coefficient equal to 16.7 ps/(nm·km), effective area equal to 80 μm^2, and a nonlinear coefficient of 1.31 $(W/km)^{-1}$. We also assume that OAs are configured to optimize QoT by maximizing the OSNR at the receiver [5].

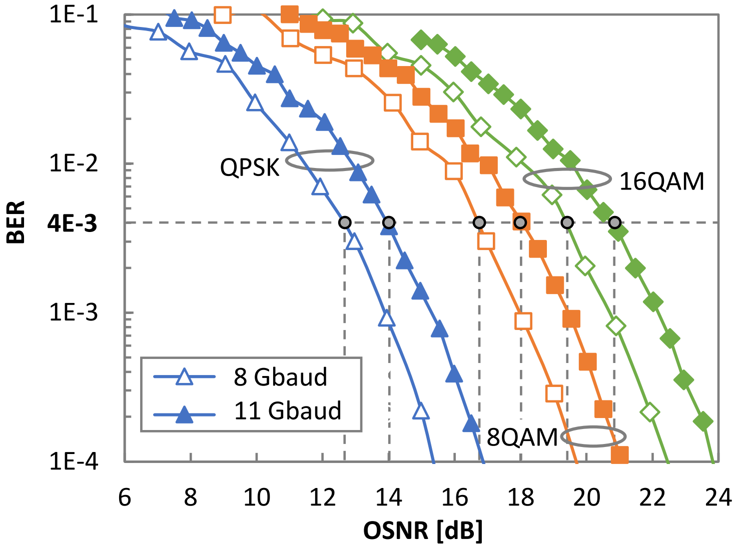
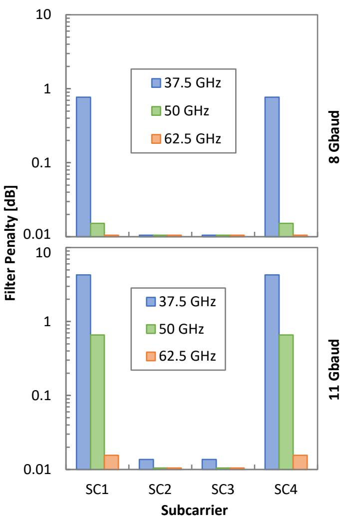


Fig. 3. BER vs OSNR for all considered SC configurations.

Figure 4 reports the evaluated filtering penalty for all four SCs and for 8 and 11 Gbd. As expected, penalties are neglectable for the internal SCs (SC2 and SC3), while are larger for the external ones (SC1 and SC4). In particular, the penalty is remarkable for 37.5 GHz slot width as the external SCs are significantly distorted by the transition band of the transfer function (32.5 GHz); in the case of 11 Gbd the penalty exceeds 4 dB.

Figure 5 presents the generalized SNR (GSNR) and the OSNR computed using an extended GNPy version [6], for one external and one internal SC as a function of the number of ROADMs in the route of the lightpath for different configurations of SR and slot width. SC2 and SC4 are not reported here as their performance are the same of SC3 and SC1, respectively. We observe that the difference between the OSNR and the GSNR is 1.76 dB, as the OLSs are working at the optimum power [5]. Moreover, the propagation impairment for the internal SC is always dominant being not affected by the number of filters. For the external SC, instead, ASE noise and NLI are the dominant impairments only for 62.5 GHz slot width and 8 Gbaud and 50 GHz slot width. In the other scenarios, filtering plays a key role and becomes the dominant impairment limiting the SC performance.

Finally, Table 3 summarizes the results for the operational limits of each SC configuration, in terms of: *i*) the minimum OSNR to guarantee pre-FEC BER threshold equal to $4 \cdot 10^{-3}$; and *ii*) the maximum number of ROADMs that can be crossed assuming that pre-FEC BER threshold. In this case, we observe that the 62.5 GHz slot width never limits the route of the lightpath. In the case of 50 GHz slot width, the maximum number of ROADMs is limited to 8 only in the case of 16QAM and 11 Gbd. Finally, in the case of 37.5 GHz, filters limit the maximum number of ROADMs, especially for 11 Gbd.



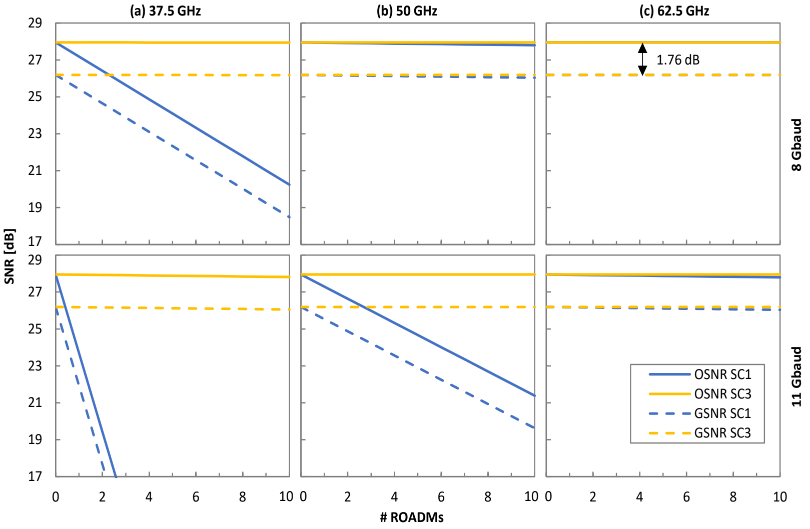


Fig. 4. Filter penalties vs SC. **Fig. 5. OSNR and GSNR at the Rx for different slot widths and SRs.**

Table 3. Minimum OSNR for threshold BER and maximum number of ROADMs due to optical filtering penalty for external SCs.

Config.	OSNR [dB]	Slot width (GHz)		
(<MF, SR>)	(BER = $4\cdot10^{-3}$)	37.5	50	62.5
QPSK, 8	12.7	10	10	10
QPSK, 11	14.0	2	10	10
8QAM, 8	16.8	8	10	10
8QAM, 11	18.1	2	10	10
16QAM, 8	19.5	8	10	10
16QAM, 11	20.8	0	8	10

Let us now analyse the accuracy of algorithm proposed for SC configuration recognition on Deliverable 3.1 [4]. Note that the target is to reach the maximum accuracy of the algorithm for scenarios with the ROADMs and OSNR values summarized in **Error! Reference source not found.**, for the different configurations.

Comparing the average distances between the received constellation and the sets of expected constellation points representing three different MFs will reveal at the Rx side the actual MF used by the Tx. However, one key aspect of the algorithm is the assumption that two configurations with the same MF and different SR will produce different average distance between the received constellation and the expected constellation points, being that with the lowest distance the one actually selected by the Tx.

Table 4 shows the distances resulting from evaluating the received constellation under the conditions in Table 3. We observe significative differences in the computed distances between the SRs, being the average distance for the right one the shortest in all cases. Note that the minimum difference is as high as 11% for <QPSK, 8> evaluated under OSNR = 12.7 dB and 10 ROADMs with 50 GHz slot width, which allows for accurate recognition even in the worse conditions. Note also that the difference increases when the OSNR increases; e.g., the difference of the distances is almost double for <16QAM, 8> evaluated under OSNR = 19.5 dB.

Figure 6 presents the results of the accuracy of recognition algorithm obtained for all configurations as a function of the OSNR. We observe that the algorithm recognizes the received configuration with 100% accuracy well below the minimum required OSNR in Table 3.

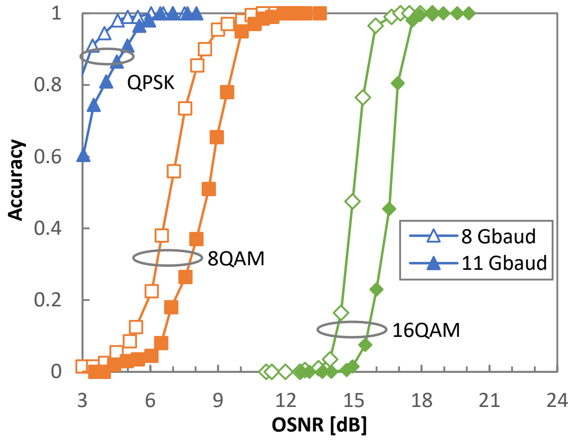


Fig. 6. Accuracy of SC configuration recognition vs OSNR.

Table 4. Average distances for SR detection.

TX / RX	**QPSK**			**8QAM**			**16QAM**		
[Gbd]	**8**	**11**	**diff**	**8**	**11**	**diff**	**8**	**11**	**diff**
8	**0.57**	0.63	11%	**0.53**	0.60	13%	**0.46**	0.55	20%
11	0.75	**0.63**	19%	0.81	**0.60**	35%	0.76	**0.54**	41%

2.4 Conclusions

Firstly, the impact of the optical filtering in hybrid filterless and filtered metro networks was investigated for fast SRs, high order MFs, and several optical channels spacing. Two scenarios were selected to capture filtering effects. The results showed that optical filtering leads to negligible OSNR penalties, lower than 1 dB, for 32 GBd signals in 50 GHz, 64 GBd in 87.5 GHz, and 96 GBd in 125 GHz. Consequently, we foresee the use of such fast SRs and high-order MFs to increase the transport capacity, which in addition, provide higher SE. The availability of such MFs and SRs will allow reducing the number of transponders, thus reducing not only capital but also operational expenses for network operators. Besides, the results show that metro/core DCs no not need to be located strictly in the metro edge, which would bring additional cost savings. All this will greatly benefit the deployment of 5G and beyond optical metro networks.

Finally, the autonomous operation of SCs has been partly presented in this report, with the objective to reduce energy consumption at the optical layer, motivated by the fact that SCs can be configured independently with the desired MF and SR. This, together with the possibility to switch off parts of the transponder directly related to each of the SC, opened an opportunity to save energy by activating only those SCs which are actually needed to support the upper layer packet traffic.

The QoT was firstly analysed, and the need to perform a per-SC estimation was introduced. The QoT estimation needs to consider not only the path and the specific SC configuration, but also the filtering penalties; the filter penalty function needs to be defined for each slot width to be allowed and depends of the specific frequency slot of the channel and the SC configuration.

2.5 References

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