Benefits of wavelength dependent reach in transparent optical networks

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Abstract *The transmission performance in WDM-systems is different for the individual WDM channels. We investigated systematically this variation and wavelength dependence by using semi-analytical simulations. The benefit of this behavior in transparent optical networks is discussed and demonstrated in network case studies.*

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1. Introduction

It has been shown before that in broadband (ultra) long haul wavelength division multiplex (WDM) transmission systems the signal reach varies for different wavelength channels [1]. In today's point-to-point systems the channel with the worst performance limits the reach. One reason for this is the different influence of the nonlinear effects on the different channels (i.e. carrier center frequencies), because these effects interact with the dispersion of the fiber. The widely deployed transmission fibers Standard Single Mode Fiber (SSMF) specified in ITU-T G.652 and Non-Zero Dispersion Shifted Fiber (NZDSF) specified in G.655 exhibit a dispersion which is lower for the channels at higher frequencies (blue channels), resulting in a higher influence of the nonlinear Kerr-effects, e.g. the four wave mixing (FWM) and cross phase modulation (XPM). Therefore, channels placed at lower frequencies (red channels) perform usually better. In addition, Stimulated Raman Scattering (SRS) effects a varying signal quality of the channels because signal power is transferred from the signals with a higher frequency ("blue channels") to the signals with a lower frequency ("red channels"). Therefore, the blue channels experience a higher effective attenuation than the red channels. Both effects contribute to a stronger degradation of the blue channels, while the red channels can even profit from them, especially from the SRS. This behavior also can was found out in [2].
We have carried out semi-analytical simulations, to determine the influence of the wavelength dependent reach. Considered are systems with 100 GHz and 50 GHz channel spacing on SSMF and NZDSF for different input powers into the transmission fiber. The results show a clear dependence of the signal quality, and thus the reach, on the used center frequency of the channels. Input powers that result in an optimized compromise between the influences of ASE and nonlinear effects as used in today's optical transmission systems make the red channels to show a remarkably higher performance than the system limiting blue channels.
Future transparent optical networks can take advantage of the dependence of the reach on the channel, i.e. routing and wavelength assignment (RWA) takes the wavelength-dependent reach of a transparent route into account. Here, the channels with better performance can bridge the long paths within the network whereas the other channels can be chosen for the shorter paths.
In this work we present the different performances (measured by the Q-factor) of the channels of an optical WDM transmission system after a certain transmission length obtained from semi-analytical simulation model. In our simulations we applied 50 GHz and 100 GHz spacing (ITU-grid) on SSMF as well as on NZDSF. In addition, we calculated the different reach for the individual channels for a given minimum Q-factor required for error-free detection of the signal. We estimate the gain of this approach in two network case studies.

2. Simulation Setups

2.1. Semi-analytical Simulations of the Optical Transmission

To study the wavelength dependent reach, simulations have been carried out for an idealistic path having equal spaced 80 km spans including equal spaced optical cross connects (OXC) after every sixth span.
For the transmission fibers the two most important types SSMF and NZDSF were chosen. The fiber parameters can be found in Table 1. For the DCF we have chosen a dispersion slope that was adapted to compensate for 100% of the transmission fiber's dispersion slope for the case of full compensation. The results of the simulations will be given in $Q_{lg} = 20 \cdot \log_{10}(Q\text{-factor})$ by different colors and lines of equal Q_{lg} in a plot reach versus frequency, where an optimum compensation for every single channel is assumed.

Parameter	SSMF G.652	NZDSF G.655	DCF
Attenuation [dB/km]	0.23	0.23	0.5
max. Raman gain [m/W]	0.3	0.5	0.56
dispersion [ps/(nm km)]	17	3.3	-85
Dispersion slope [ps/(nm² km)]	0.085	0.045	100%
Nonlinear refractive index [10^{-20} m²/W]	1.4	1.36	1.36
Effective core area [µm²]	35.7	55	14.1

Table 1 Fiber parameter used in the simulations

The dispersion map applied within the simulations is shown in Figure 1. The pre-compensation was –340 ps/nm, for each span the accumulated dispersion was increased by 50 ps/nm. At each node, the dispersion was reset to the original value of -340 ps/nm.

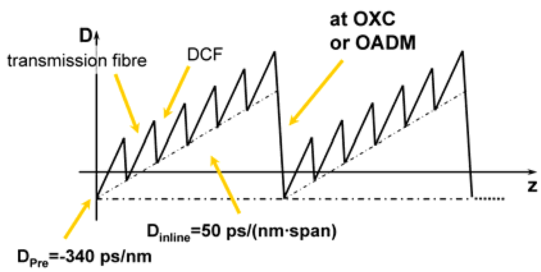

Figure 1: Schema of the dispersion map applied within the simulations

We simulated both, an 80 channel system with channel spacing of 50 GHz and a 40 channel system with channel spacing of 100 GHz. The outer channels were at 191.7 GHz and 196.1 GHz. In between 193.75 GHz and 194.05 GHz there is no active transmission channel but a "gap" in the transmission spectrum.

In order to get a notion, which channels suffer more or less from the transmission, we simulated the Q-factor of the following 8 channels: 191.7 THz, 192 THz, 192.6 THz, 193.3 THz, 194.5 THz, 195.2 THz, 195.8 THz, and 196.1 THz. A few simulations were carried out for all channels. These simulations show a good agreement between the interpolated and the simulated values. No significant outliner could be observed.

The signal impairment by the nodes was assumed to be attenuation only, i.e. a contribution to the OSNR of the transmission system. Accordingly, each node contributes with an OSNR-penalty corresponding to a span with an attenuation of 12 dB. Note that transmitter and receiver nodes do not contribute by further attenuation.

The system performance is expressed by the Q-factor. The Q-factor calculation based on the "Marcuse-Method" as described in [3] is performed for different residual dispersion values after every span, to estimate the dispersion tolerance of the system at these positions. The performance is then given in dB with $Q_{lg}=20\cdot\log_{10}$(Q-factor).

For the non-linear effects semi-analytical models were applied. SPM contributions were determined numerically using the split step Fourier-transform method. XPM distortions were calculated analytically using the model described in [4]. To determine the FWM power within the filter bandwidth of the channel of interest, all relevant channel combinations are regarded. For every channel combination, the generated FWM field on subsequent spans is summed coherently. Finally, the FWM power contributions from different channel triplets are summed at the end of the system.

For SRS, only the mean power transfer was considered. Spectral tilt was pre-compensated at each amplifier to guarantee a tilt-free WDM comb at the input of the following amplifier. For SRS only the Raman tilt was included which then was compensated at the beginning of each amplifier span in order to avoid an accumulated Raman tilt.

The simulation has been carried out for non-return-to zero on-off keying modulation format (NRZ) with cos²-signal with an initial OSNR of 50 dB and an extinction ratio of 20 dB. The signal generation was simulated as combination of a DFB laser and a MZM in push-pull operation. For the receiver characteristics we applied an optical filter with a bandwidth of 25 GHz, an electrical filter of 14 GHz and allow for a timing jitter of 20 ps, i.e. the minimum extinction ratio within the receiver eye over a time slot of 20 ps was chosen for the performance calculation.

As a further parameter the input power in the transmission fiber was varied. In order to identify the input power chosen for each span we introduced the input power per channel normalized to the attenuation of a 100 km span length, P_{N100}. This is the power needed to be inserted into the transmission link per channel if the transmission link has a length of exactly 100 km. For spans with a different length, and thus a different attenuation, the input power was chosen to be

$$P_{in}(\alpha(z)) = P_{N100} + \tfrac{1}{2}(\alpha(z) - \alpha(100\text{km}))$$

where α is the attenuation in dB and P the power in dBm. The power into the DCF was chosen to be

$$P_{DCF} = \tfrac{1}{2} P_{N100} - 4\text{dB}$$

with the powers in dBm. The EDFA noise figure was 7 dB with a wavelength independent gain and noise figure. Note that this simplification is significant regarding the wavelength dependency of performance.

Throughout the simulations polarization mode dispersion (PMD) and filter effects were neglected. It is assumed that the limitations of the transmission reach, and especially the dependence of the performance on the wavelength, is due to the non-linear effects and OSNR. For filter effects this assumption can be justified for 10 Gbit/s systems and channel spacing of 100 GHz and 50 GHz. For PMD it is known that this effect might cause strong distortions preventing error free detection. Typically, a differential group delay (DGD) of 10% of the data rate should not be exceeded, e.g., the DGD is 10 ps in a 10 Gbit/s transmission. Assuming a PMD coefficient of the transmission fiber of 0.2 ps/(km)$^{1/2}$, a transmission distance of about 2500 km can be covered for a PMD of 10 ps. Since PMD is a temporal statistical effect, also higher DGD values might occur during certain periods leading to errors in the transmission. However, since this effect is of statistical nature and does not depend on the wavelength, we do not take this effect into account for the study presented here. Several studies have been presented in the past giving probability density functions for system outages under the presence of PMD [5, 6].

With this approach (neglecting the impact of filter, PMD and application of an ideal EDFA) we study the wavelength dependency irrespective of specific properties of the system, like PMD parameter of the links or EDFA properties (which usually also are subject of the operation conditions). It has to be kept in mind that for implementation of the presented results, the neglected system-specific parameters have to be considered. The present study shows the principal behavior and real-world networks need of course further individual adaptation.

2.2. Network Case Studies

To demonstrate the benefit of wavelength dependent reach in transparent networks the results for the physical layer are used in network simulations. We aim to present the gain that can be achieved in terms of more satisfiable demands if wavelength dependent routing algorithms are applied.

Among the considered networks we explain the methods in the network case studies for the Deutsche Telekom network, see Figure **2**. The network is modeled as an undirected graph $G(V,A)$, where V is the set of vertices describing the nodes of the network and A the set of edges describing the links in the network. Every edge represents a physical link between two nodes of the network and is characterized by its length.

The network has to satisfy demands, i.e. wavelength connection requests between nodes. To demonstrate the benefit of wavelength dependent reach, we set up the demands using one of the following routing algorithms:

- Shortest path routing without protection, using the Djikstra algorithm on $G(V,A)$. The output is a path with minimum length between two nodes.
- Shortest pair of node-disjoint paths routing for 1+1 node-disjoint protection, using the Bhandari algorithm [7] on $G(V,A)$. The output is a pair of node-disjoint paths between two nodes with minimum sum of the paths' lengths.

There are two approaches to calculate the number of spans for a given path. In the first one, we measure the whole distance, divide it by 80 km (which is assumed to be the optimal span length) and apply the rounding function. The drawback of this approach is that it does not capture the physical topology constraints. This can be illustrated in the Network of the Deutsche Telekom (Figure **2**). The shortest path between Düsseldorf and Hannover is 244 km long (Düsseldorf-Essen-Dortmund-Hannover). Dividing 244 km by 80 km and applying rounding results in 3 spans. But a realistic network implementation will result in 4 spans (1 for Düsseldorf-Essen, 1 for Essen-Dortmund and 2 for Dortmund-Hannover).

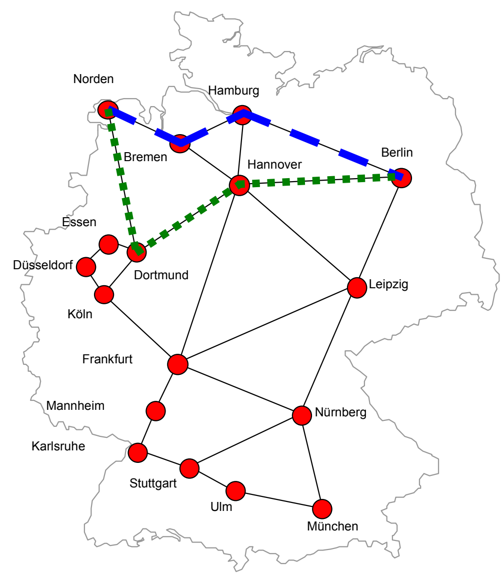

Figure 2: Deutsche Telekom network

This second approach is to calculate the number of spans for every single link as discussed above and then the path length is calculated as a sum of the spans for every link on the path. As this modeling is close to realistic networks, we use this second approach.

The shortest path algorithm and the shortest pair of paths algorithm calculate the path length as the sum of the number of spans that are traversed by the path. This is easily done by setting the link metrics to the number of spans. To additionally model the physical penalty of a node, we assume that passing through an intermediate node enlarges the path length by one span. This can be modeled by increasing the links' number of spans by one. The algorithms can run on these link metrics and they provide the desired results if the computed paths lengths are afterwards diminished by one span.

Once the link metrics are set and a routing algorithm is chosen we route the demands and calculate their length in spans. Then we compute a cumulative distribution function (cdf) for length of the demands paths. The x-axis is the number of spans as a distance measure and the y-axis is the total number of paths with the same or greater distance. In 1+1 node-disjoint protection, we use the longer path of the path pair.

As an example we consider the demand between Norden and Berlin (see Figure **2**). If 1+1 node-disjoint protection is assumed, we need to find a pair of disjoint paths. The Bhandari algorithm computes this path pair resulting in 18 as minimum sum of the paths' lengths. The first path is Norden-Bremen-Hamburg–Berlin with length 8 spans and the second one is Norden-Dortmund-Hannover-Berlin, with length 10 spans. We use the second path with the longer length of 10 for the cdf.

3 Wavelength Dependence in Optical Transmission Systems

The intention of this study is to get information about the wavelength dependence of the performance or, similar, the reach of the individual channels of a WDM system. As mentioned above, traditional point-to-point transmission systems had to be designed such that the worst channel is error free after transmission. This can be different for future transparent optical networks: Advanced wavelength assignment along with different reach of the individual channels can be used to bridge higher distances than possible with today's point-to-point systems. The channels whose performance suffers less from the transmission will be used for the longest distances to bridge, whereas the channels with a stronger degradation of performance will be used for the shorter paths within the transparent domain.

As a general tendency the lower frequency channels ("red" side) show a better performance than the channels on the "blue" side of the simulated spectrum. Therefore we separate the spectrum of the WDM signal and refer to the "low frequency channels" (LFC) and the "high frequency channels" (HFC).

The threshold for acceptable performance was set for a Q-factor of 7, or Q_{lg}≥17 dB. It turns out, that in these simulations for the presented parameters for a long haul distance of 2000 km the required Q_{lg}≥17 cannot be reached for 80 channel systems, except for a single configuration (G.655 fiber, P_{N100}=3 dBm, for 191.7 THz, 192 THz, and 192.6 THz, i.e. only for some of the LFCs) with a very narrow dispersion tolerance for the respective Q_{lg}. For 40 channel systems the situation is more relaxed, for several configurations of the simulations a Q_{lg}≥17 dB is visible for a reach of more than 2000 km corresponding to 25x80 km spans.

It can clearly be seen from Figure **3** that for an 80 channel ultra long haul WDM system the channel's performance or reach depends strongly on the frequency. In general, the dependence on the wavelength seems to be higher for the G.655 fiber whereas for the G.652 fiber there are several configurations for which the performance is relatively homogeneous for all channels especially for 40 channel (100 GHz spacing) configurations. Common for nearly all simulations is a minimum performance and dispersion tolerance for the channel at 195.8 THz. It is interesting to note that the outer channel on the HFC side of the spectrum shows again a better performance as this "bottleneck". The outer channel profits from the reduced inter-channel non-linear effects because there are no neighbor channels on one side of the channel.

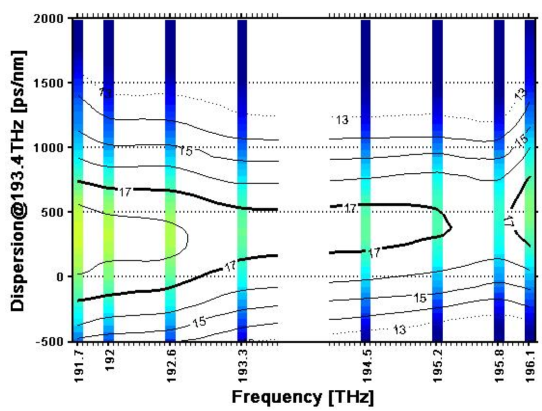

Figure 3: Dispersion tolerance vs. frequency for a 50 GHz spacing transmission via 20x80 km SSMF with a P_{N100} of 3 dBm. The channel at 195.8 GHz is the "bottle-neck" for today's point-to-point systems not reaching a Q_{lg} of 17 dB. The 191.7 GHz channel tolerates a range of nearly 1000 ps/nm for this performance.

As a conclusion, for transmission over more than 1500 km it is strongly recommended to choose a set of appropriate wavelengths in combination with a powerful FEC. For all results it has to be kept in mind that the simulated Q-factors have to be interpreted as relative results and not as absolute values for an arbitrary transmission system for which additional system specific constraints, like EDFA frequency dependent gain and noise figure and PMD parameters of the fiber links, have to be considered. Despite, it can be assumed that the presented result represent very well the ratios appearing in a real WDM system.

3.1 Simulation Results for 100 GHz spacing

The best performance for a 40 channel system with 50 GHz spacing over NZDSF can be obtained for a nominal power into the transmission fiber P_{N100} of 3 dBm. For the threshold value for systems without FEC of Q_{lg}=17 dB the results show that up to 27x80 km spans can be bridged by all channels. Even for the harder requirement of a dispersion tolerance of 340 ps/nm at the end of a system with an OXC at the end of every third span a Q_{lg}>17 dB for at least 25 spans should be possible for the worst channel. This limiting channel here is at 195.8 THz and turned out to be the most critical one in the simulation series discussed here. The other channels on the HFCs also have a visible 17 dB limit in the observed area up to 36 spans. The limits for the blue channels of this configuration are above this area.

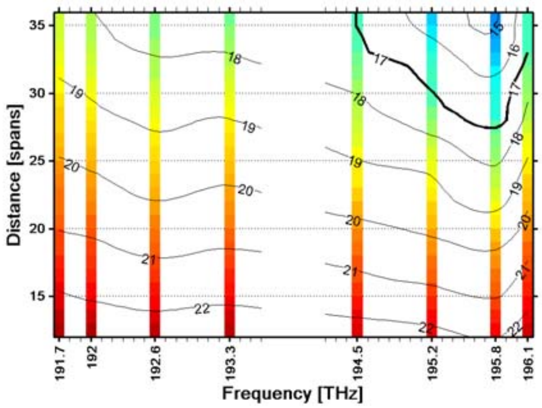

Figure 4: The maximum Q_{lg} for a 100 GHz channel spacing transmission over NZDSF with a per channel P_{N100} of 3dBm.

When SSMF is used as transmission fiber the reach for a system without FEC enhances to more than 30 spans for all channels at an increased P_{N100} of 6 dBm. It can be found that the channels of the blue sub-band have a worse performance than the others but still have a reach above 30 spans. Considering a dispersion tolerance margin of 340 ps/nm the reach is reduced by 2 spans in the worst case for powers of P_{N100} greater than 0 dBm.

3.2 Simulation Results for 50 GHz spacing

80 channels with 50 GHz spacing seem to be a less suitable configuration for (ultra) long haul transmission due to the mentioned sensibility to inter channel nonlinearities of the NZDSF caused by its small dispersion coefficient.

SSMF is best for carrying 80 channels with a channel-spacing of 50 GHz over long haul distances. For 3 dBm nearly 20 spans can be bridged with a Q_{lg} of 17 dB for all channels. Taking a dispersion tolerance of 340 ps/nm and an OXC after every 3rd span into account still 19 spans should be possible.

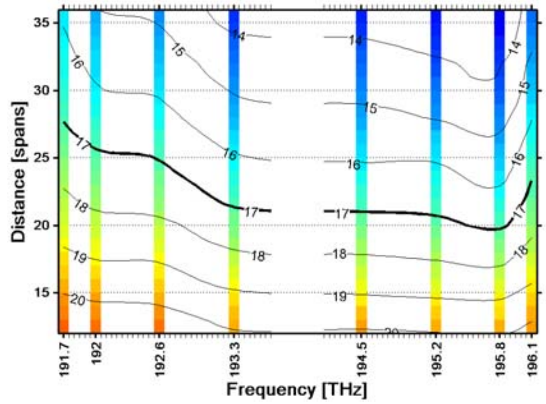

Figure 5: The maximum Q_{lg} for a 50 GHz channel spacing transmission over SSMF with a per channel P_{N100} of 3dBm.

The number of channels able to reach a certain number of 80 km spans according to our simulations can be found in Figure **7** for a minimum Q_{lg} of 17 dB for SSMF and NZDSF. In case a lower Q_{lg} of 15 dB can be tolerated by the system these values are given in Figure 8. The latter can be the case when applying a powerful forward error correction or equalizer at the receiver.

4 Taking Advantage of the Wavelength Dependent Reach

The simulation results presented above, show that the reach of several channels of an optical long haul transmission system is significantly reduced compared to other channels. In today's point to point configurations these channels limit the reach of the complete WDM system.

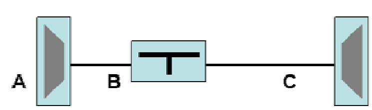

Figure 6: Simple network configuration which is already capable to benefit from wavelength dependent reach.

When considering networks which include switching in the optical layer the wavelength with only a short reach (according to the simulations in chapter 3 the HFCs) can be assigned for wavelength services of shorter distance whereas the LFCs can be used to bridge longer distances without regeneration in the electrical domain. In such a simple network configuration as shown in Figure 6 the wavelength dependent reach can already be applied. If we assume that the distance between nodes A and B and between nodes B and C is 900 km each the LFC can bridge the total distance of 1800 km whereas for most HFC the performance is not sufficient. Therefore, the HFC will then be used to transport the date from node A to node B, node B to node C, or vice versa.

4.1 Results for the Deutsche Telekom Network

To show the benefit of wavelength dependent reach in all optical networks, the simulation results are applied to routing of demands in a network. For the analysis, the topology of the network of Deutsche Telekom shown in Figure 2 is used. Figure 7 shows the results.

The reach of a traditional system limits any path to 20 and 14 spans in networks with SSMF and NZDSF, respectively. The figure shows the wavelength-dependent reach of SSMF by the lines with black rectangles and of NZDSF by the lines with red disks, assuming an 80 channel system with 50 GHz channel spacing.

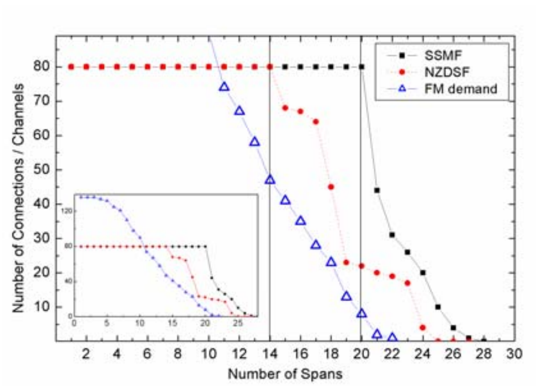

Figure 7: Number of possible demands for the full mesh Deutsche Telekom network with 1+1 protection and the number of channels capable to reach a certain number of spans according to our simulations presented above.

This per-channel visualization is compared with the path length cdf for a full mesh (FM) demand. As a FM demand has one connection request between each node pair, we can interpret this cdf as follows: If we give a certain span length and pick a random node pair, and thus a random demand which we want to satisfy, the probability that the demand is routed over the given span length is its value at the cdf. We assume that demands are routed only on the shortest path or on the shortest pair of paths. For the DT network we consider the case of 1+1-protected demands where the longer path of the two disjoint paths determines the feasibility of a connection and is used in the cdf.

The figure includes the histogram-representation of the cdf by the line with blue triangles. We see that 2 and 41 node pairs can take advantage of the longer reach, for SSMF and NZDSF, respectively.

We also can conclude that, both for 1+1-protected and implicitly for unprotected demand, regeneration can be fully avoided for the given routing if wavelength conflicts are not present. Note that wavelength conflicts only occur if paths share the same fiber. The “FM demand” curve is obtained by routing in the entire network, where wavelength reuse applies for non-sharing paths. Moreover, wavelength conflicts are often resolved by longer paths, which is in favor of the reach-enhanced wavelengths.

4.2 Results for the British Telecom core network

When it is possible to implement a feature like a FEC algorithm that allows a reduced signal quality at the receiver by keeping the BER constant, the considerations for the DTAG network also can be applied on more extended networks like the core network of the British Telecom. The demands for the network and the system limitation for the case that a Q_{lg} reduced by 2 dB is sufficient can be seen in Figure 8. Whereas the FM demand without protection might be fulfilled for NZDSF at a suitable blocking ratio, protection here only is possible when SSMF is used as fiber type for the transmission fiber. In the first case 182 demands would benefit from the application of wavelength dependent reach when NZDSF is applied, for SSMF only 2 demands need this system improvement. For the second case including protection 75 demands would need wavelength dependent reach for allowing a transparent network.

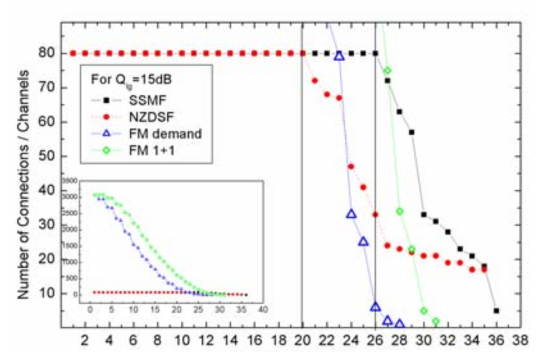

Figure 8: Number of demands for the full mesh BT network with and w/o 1+1 protection and the number of channels capable to reach a certain number of spans according to our simulations for a reduced performance requirement of Q_{lg}=15 dB.

5 Conclusion

It has been shown that the varying performance of the different channels caused by the effects in the transmission fiber is remarkable for long haul systems above 1000 km. The reach of the best channels is up to about 1.5 times higher than for the worst channel in typical configurations. This fact can be used applying intelligent algorithms in the routing and wavelength assignment of transparent optical networks.

The benefit of wavelength dependent reach in two networks has been shown to be remarkable. It has been shown that for example for the Deutsche Telekom network regenerators can be fully avoided taking the wavelength dependence into account.

6 Acknowledgement

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7 References

1. Christian Malouin, Alan Solheim, Greg Friesen, Vivek Ramaswami, Steve Goeringer, "Verifying agile transparent system performance with field testing", Proceedings of OFC, Los Angeles 2004, paper WP2

2. Michael Vasilyev, Ioannis Tomkos, Manjusha Mehendale, June-Koo Rhee, Andrey Kobyakov, Mahesh Ajgaonkar, Sergio Tsuda, and Manish Sharma, "Transparent ultralong-haul dwdm networks with broadcast-and-select oadm/oxc architecture", Journal of Lightwave Technology, Vol.21 No.11 (2003) pp2661

3. Dietrich Marcuse. "Calculation of bit-error probability for a lightwave system with optical amplifiers and postdetection gaussian noise", Journal of Lightwave Technology Vol.9 No.4 (1991) pp505

4. Gernot Goeger, Marc Wrage, and Wolfgang Fischler, "Cross-phase modulation in multispan wdm systems with arbitrary modulation formats", IEEE Photonics Technology Letters, Vol.16 No.8 (2004) pp1858

5. Magnus Karlsson, "Probability Density Functions of the Differential Group Delay in Optical Fiber Communication Systems", Journal of Lightwave Technology, Vol.19 No.3 (2001) pp324

6. P.J. Winzer, H. Kogelnik, and K. Rmanan, "Precise Outage Specifications for First-Order PMD" IEEE Photonics Technology Letters, Vol. 16 No.2 (2004) pp449

7. Ramesh Bhandari. Kluwer Academic Publishers "Survivable Networks – Algorithms for Diverse Routing",1999, Chapter 7