Impact of Adaptive-Rate Transponders and Fiber Attributes on the Achievable Capacity

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***Abstract*—We use the analytical Gaussian noise model to assess the achievable capacity over a fully transparent network with 18 nodes and 26 physical connections. By applying a network-centric approach, we show that the use of adaptive modulation in combination with ultralow loss fiber can provide an increase in the achievable capacity. The use of ultralow loss, large effective area fibers can allow for further capacity increase.**

***Index Terms*—Optical fiber networks; Telecommunication network topology.**

I. Introduction

As demand for bandwidth incessantly grows [1] and nodes in core networks continue to consolidate [2], transmission capacity in backbone optical links is becoming a scarce resource. To address this issue, research groups have focused on increasing the spectral efficiency (SE) by utilizing higher-order modulation formats, in conjunction with digital coherent detection [3,4]; reducing the spacing between the wavelength channels; and finding other creative ways to manage the available optical bandwidth [5]. One such technique involves adaptive modulation, which has been widely used in wireless communications but is less common in the optical fiber domain. Adaptive modulation provides benefits by maximizing the achievable capacity for a given distance [6], and its impact on optical network traffic gain has been studied in [7].

In this work we compare the performance of several optical fibers in terms of maximum reach and achievable capacity in a scenario that involves adaptive modulation. To carry out this analysis we have used physical layer modeling over a backbone network in Germany with a fully transparent architecture. For a fixed-rate 200 Gb/s PDM-16QAM 80-km-span transmission, we show that Corning SMF-28 ULL fiber can cover 96% of all connections in the network without electrical regeneration, while the legacy fiber only covers 24%. For an adaptive-rate 80-km-span transmission, SMF-28 ULL fiber is found to provide a 45% increase in achievable capacity relative to a legacy fiber. The use of Corning Vascade EX2000 fiber enables a 60% increase in capacity, also relative to a legacy fiber. An impact of changing the span length to 40 km or 120 km is also studied.

II. Network, Fiber, and System Attributes

We base our capacity calculations on the Gaussian noise (GN) model [8,9], which we have applied to an exemplary backbone network topology in Germany. It comprises 18 nodes, each of which is equipped with a core router operating on a fully meshed IP layer and interconnected by 26 links on the WDM layer, as shown in Fig. 1. To facilitate network survivability on the underlying aggregation level, a dual-homing approach has been applied, resulting in two core nodes per point of presence. The core network is fully transparent, so traffic is routed on the WDM layer without electrical regeneration. Each node with a nodal degree of 2 is equipped with an optical add–drop multiplexer (OADM), while each node with a nodal degree >2 is equipped with an optical cross connect. We assume that the shortest route for each connection will be the main path, while the second shortest, geographically diverse (where possible) route will be the protection path.

All transmission links are free of dispersion compensating fiber, and their lengths are assumed to be 30% longer compared to the straight-line distance to account for realistic cable deployment conditions. The amplifier spacing has been varied between 40, 80, and 120 km, while the erbium-doped fiber amplifier (EDFA) noise figure was assumed to be 5 dB. Furthermore, we have analyzed the performance of three different fiber types: legacy single-mode fiber (representative of the current Deutsche Telekom network), SMF-28 ULL fiber, and Vascade EX2000 fiber, with fiber parameters given in Table I. We assume that the cabled attenuation of new fibers will be the same as fiber attenuation. To provision for additional loss stemming

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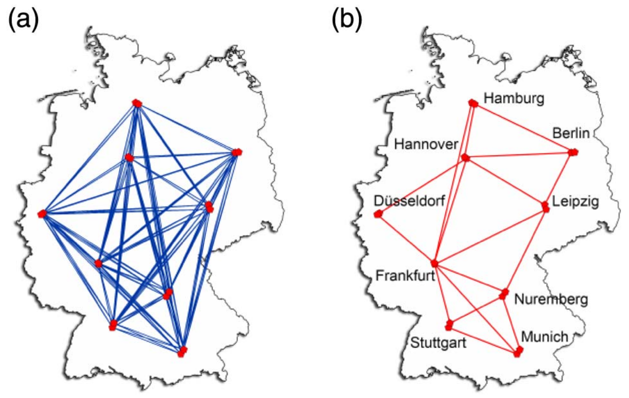

Fig. 1. Topology of (a) IP layer and (b) WDM layer.

TABLE I
PARAMETERS OF FIBERS USED IN THIS STUDY (AT 1550 NM)

	Legacy Fiber	SMF-28 ULL Fiber	Vascade EX2000 Fiber
Attenuation (dB/km)	0.25	0.165	0.159
A_{eff} (μm^2)	82	82	112
n_2 (m^2/W)	2.3×10^{-20}	2.1×10^{-20}	2.1×10^{-20}
Gamma (1/W/km)	1.14	1.04	0.76
Dispersion (ps/nm/km)	17	17	20.3

from installation of the fiber cable as well as potential cable cuts/repairs along the link, we assume a cable drum length of 4 km with additional splice loss of 0.05 dB between any two cable sections (excluding the legacy fiber case), an end-of-life span loss margin of 3 dB/100 km, and 0.25 dB connector loss at the transmitter and receiver.

With these boundary conditions, the network contains 306 bidirectional transparent connections with the shortest path being only 5 km and the longest one 1482 km. Note that the condition of having geographically diverse protection paths leads to a much wider distribution of the path lengths. We also assume that each of those transparent connections is fully filled with 150 Nyquist WDM channels, creating a worst-case scenario with maximum nonlinear distortion for the individual WDM channel. Those channels are spaced at 32 GHz, leading to an overall optical bandwidth of 4.8 THz, which corresponds to the amplification C-band of commercially available EDFAs [10,11]. The losses of OADMs are neglected in this study.

Each adaptive-rate transponder operates at a symbol rate of 32 GBaud and can generate net bitrates between 50 and 500 Gb/s by varying the modulation formats from PM-BPSK to PM-1024QAM. Furthermore, we assume that each of those transponders has an additional vendor Q-margin of 3 dB. Note that in reality there is an additional implementation penalty that usually increases with the modulation density. However, since those penalties are constantly improving, especially as photonic integration, the quality of electronics, and digital signal processing get better, we have neglected this influence in our work to study the upper limits of transmission performance instead.

III. RESULTS AND DISCUSSION

As a first step, we use the GN model to calculate the maximum reach for a given modulation format and for the three different fibers, as shown in Table II. We assume a span length of 80 km, which represents a typical span length in the Deutsche Telekom network in Germany. It is apparent that for any given distance, SMF-28 ULL fiber enables the use of higher-density modulation compared to a legacy fiber, thus resulting in a higher bitrate. Furthermore, Vascade EX2000 fiber provides additional capacity enhancement windows relative to SMF-28 ULL fiber.

For example, at 1400 km, Vascade EX2000 fiber supports 200 Gb/s PM-16QAM transmission, while in the case of SMF-28 ULL fiber, this is limited to 150 Gb/s PM-8QAM, resulting in a 33% increase in achievable capacity per transponder pair. Similarly, at 700 km, Vascade EX2000 fiber supports 250 Gb/s PM-32QAM transmission, while SMF-28 ULL fiber supports only 200 Gb/s PM-16QAM (a 25% increase in capacity).

We now apply the maximum reach for each individual fiber type to the transparent paths within the network, initially assuming that fixed-rate 200 Gb/s PM-16QAM transponders are used. Figure 2 shows the distribution of bidirectional transparent connections in the network, with the granularity on the x axis chosen to represent

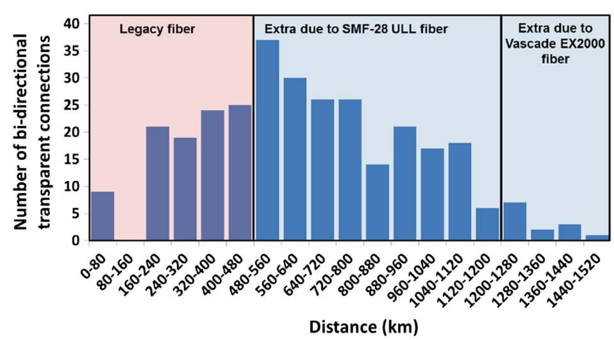

Fig. 2. Histogram of transparent connection lengths and coverage by fiber type at 200 Gb/s (PM-16QAM).

TABLE II
MAXIMUM REACH (KM) FOR SEVERAL FIBERS AT DIFFERENT MODULATION FORMATS (80 KM SPANS)

	PM-QPSK	PM-8QAM	PM-16QAM	PM-32QAM	PM-64QAM	PM-128QAM	PM-256QAM
Legacy fiber	2720	1120	480	240	80	0	0
SMF-28 ULL fiber	6160	2640	1200	560	240	80	0
Vascade EX2000 fiber	8560	3680	1680	800	400	160	80

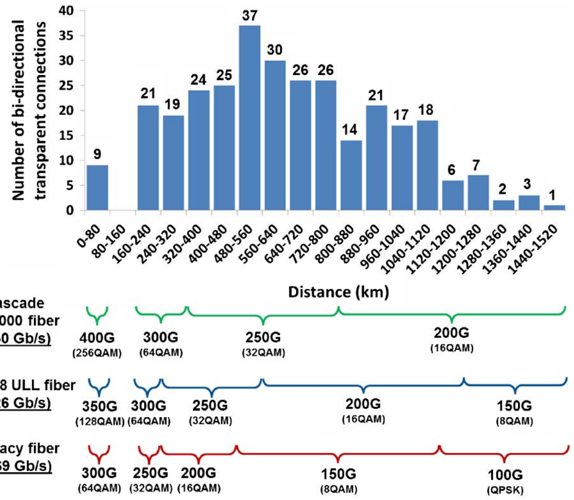

Fig. 3. Maximum achievable modulation density for each of the transparent connections in the histogram (80 km spans).

integer multiples of the span length. The figure illustrates the fact that legacy fiber covers only 32% of the connections at 200 Gb/s without intermediate regeneration, while SMF-28 ULL and Vascade EX2000 fiber can increase the coverage to 96% and 100%, respectively.

In the configuration involving adaptive-rate transponders, we can identify the highest achievable modulation density (hence, net bitrate per transponder pair) that can be transmitted over each of the 306 transparent bidirectional connections. Such a large number of connections reflects the fact that in a fully transparent network, traffic needs to be able to originate from any node to any other node on the map. The maximum achievable capacity per transponder, averaged over all bidirectional transparent connections (further denoted as “mean transponder capacity”), provides an indication about the achievable capacity in the network (Fig. 3).

Figure 3 uses the maximum reach values from Table II to identify the number of connections that can be covered with different modulation formats. For example, SMF-28 ULL fiber can cover nine transparent connections at 350 Gb/s, 21 connections at 300 Gb/s, 105 connections at 250 Gb/s, 158 connections at 200 Gb/s, and 13 connections at 150 Gb/s. The mean transponder capacity is, therefore, 226 Gb/s. Following similar methodology, the mean transponder capacity for Vascade EX2000 fiber was found to increase to 250 Gb/s, and, in the case of legacy fiber, the mean transponder capacity decreases to 169 Gb/s.

One way to increase the mean transponder capacity for each of the fiber types is to decrease the span length from 80 to 40 km. This will increase the optical signal-to-noise ratio (OSNR) and, therefore, for any given modulation scheme will also enable longer reach (Table III), ultimately leading to an increase in mean transponder capacity, as shown in Fig. 4. The granularity on the x axis is chosen to represent integer multiples of a 40 km span. The mean transponder capacity is calculated to be 246 Gb/s for a legacy fiber, 274 Gb/s for SMF-28 ULL fiber, and 292 Gb/s for Vascade EX2000 fiber. It must be noted that 40 km spans will result in additional maintenance, temperature, and humidity control for the amplifier huts.

On the contrary, increasing the span length from 80 to 120 km will decrease OSNR, leading to a reduction in maximum reach (Table IV) and mean transponder capacity (Fig. 5). However, this also reduces the number of active amplifier huts, which may represent an attractive path forward in case a reduction in cost is more important than an increase in capacity (e.g., for networks with modest traffic demand values). The mean transponder capacity is found to be 88 Gb/s for a legacy fiber, 168 Gb/s for SMF-28 ULL fiber, and 193 Gb/s for Vascade EX2000 fiber.

Table V uses the data from Tables II–IV to show the change in mean transponder capacity when decreasing the span length from 80 to 40 km or increasing the span length from 80 to 120 km. The results show that ultralow loss fibers provide a higher-capacity benefit for longer spans. In the case of 120 km spans, all three fibers experience a reduction in the mean transponder capacity. However, SMF-28 ULL and Vascade EX2000 fibers limit such reduction to a minimum.

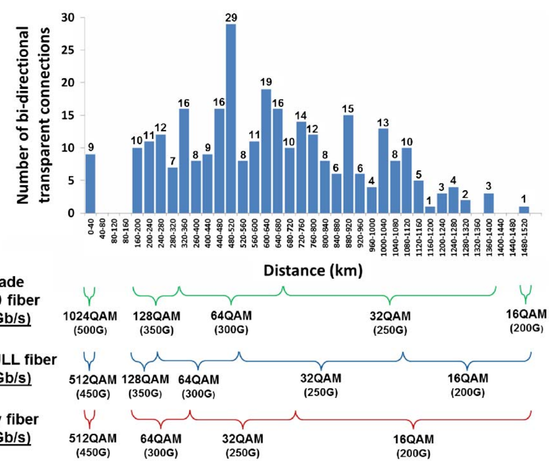

Fig. 4. Maximum achievable modulation density for each of the transparent connections in the histogram (40 km spans).

TABLE III
MAXIMUM REACH (KM) FOR SEVERAL FIBERS AT DIFFERENT MODULATION FORMATS (40 KM SPANS)[a]

	PM-8QAM	PM-16QAM	PM-32QAM	PM-64QAM	PM-128QAM	PM-256QAM	PM-512QAM
Legacy fiber	3280	1520	720	360	160	80	40
SMF-28 ULL fiber	4840	2240	1080	520	240	120	40
Vascade EX2000 fiber	6440	3000	1440	680	320	160	80

[a]Vascade EX2000 fiber reaches 40 km at PM-1024QAM.

TABLE IV
MAXIMUM REACH (KM) FOR SEVERAL FIBERS AT DIFFERENT MODULATION FORMATS (120 KM SPANS)[a]

	PM-BPSK	PM-QPSK	PM-8QAM	PM-16QAM	PM-32QAM	PM-64QAM
Legacy fiber	2160	720	240	120	0	0
SMF-28 ULL fiber	7680	2520	1080	480	240	120
Vascade EX2000 fiber	11,160	3720	1560	720	360	120

[a]The modulation formats in Table IV are different from the ones in Table III.

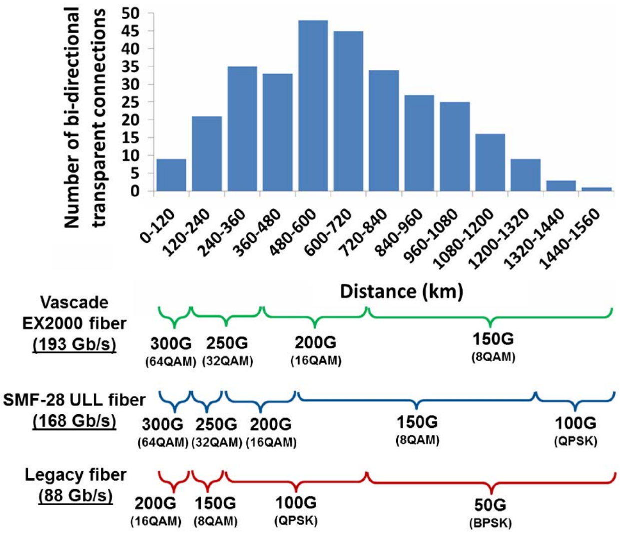

Fig. 5. Maximum achievable modulation density for each of the transparent connections in the histogram (120 km spans).

TABLE V
CHANGE IN MEAN TRANSPONDER CAPACITY WITH A CHANGE IN SPAN LENGTH FOR THREE DIFFERENT FIBERS[a]

	Legacy Fiber (%)	SMF-28 ULL Fiber (%)	Vascade EX2000 Fiber (%)
80 km → 40 km	+46	+21	+17%
80 km → 120 km	−48	−26	−23%

[a]Percentage is calculated as [100 × (Capacity X− Capacity 80 km)]/Capacity 80 km.

IV. CONCLUSION

For a fixed-rate 200 G 80-km-span transmission in the German network, SMF-28 ULL fiber significantly increased the number of transparent links covered without intermediate regeneration (from 32% to 96%, relative to a legacy fiber). For a flexible-rate 80-km-span transmission, SMF-28 ULL fiber enabled higher-mean-transponder capacity (i.e., the average capacity that can be "squeezed out" from the transponder) of 226 Gb/s relative to 169 Gb/s achieved in the case of legacy fiber. Vascade EX2000 fiber increased the mean transponder capacity to 250 Gb/s. An increase in mean transponder capacity translates into a comparable increase in network capacity. We also studied the impact of changing the span length to 40 km to enable even higher capacities and to 120 km to lower the number of amplifier huts.

REFERENCES

[1] "Cisco Visual Networking Index: Forecast and Methodology, 2013–2018," June 2014 [Online]. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/ip-ngn-ip-next-generation-network/white_paper_c11-481360.pdf.

[2] R. Huelsermann, M. Gunkel, C. Meusburger, and D. A. Schupke, "Cost modeling and evaluation of capital expenditures in optical multilayer networks," *J. Opt. Netw.*, vol. 7, no. 9, pp. 814–833, 2008.

[3] S. J. Savory, G. Gavioli, R. I. Killey, and P. Bayvel, "Electronic compensation of chromatic dispersion using a digital coherent receiver," *Opt. Express*, vol. 15, no. 5, pp. 2120–2126, 2007.

[4] X. Zhou and J. Yu, "Multi-level, multi-dimensional coding for high-speed and high-spectral efficiency optical transmission," *J. Lightwave Technol.*, vol. 27, no. 16, pp. 3641–3653, 2009.

[5] O. Gerstel, I. Cisco, M. Jinno, A. Lord, and S. J. B. Yoo, "Elastic optical networking: A new dawn for the optical layer?" *IEEE Commun. Mag.*, vol. 50, no. 2, pp. s12–s20, 2012.

[6] X. Zhou, L. Nelson, and P. Magill, "Rate-adaptable optics for next generation long-haul transport networks," *IEEE Commun. Mag.*, vol. 51, no. 3, pp. 41–49, 2013.

[7] S. Korotky, R.-J. Essiambre, and R. W. Tkach, "Expectations of optical network traffic gain afforded by bit rate adaptive transmission," *Bell Labs Tech. J.*, vol. 14, no. 4, pp. 285–295, 2010.

[8] A. Splett, C. Kurtzke, and K. Petermann, "Ultimate transmission capacity of amplified optical fiber communication systems taking into account fiber nonlinearities," in *Proc. ECOC*, 1993, vol. 2, pp. 41–44.

[9] P. Poggiolini, A. Carena, V. Curri, G. Bosco, and F. Forghieri, "Analytical modeling of nonlinear propagation in uncompensated optical transmission links," *IEEE Photon. Technol. Lett.*, vol. 23, no. 11, pp. 742–744, 2011.

[10] Alcatel-Lucent 1626 light manager, specifications.

[11] Enhanced C-Band 96-Channel EDFA Amplifiers for the Cisco ONS 15454 MSTP, specifications.