Optical Networking Beyond WDM

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Manuscript received February 15, 2012; accepted February 19, 2012. Date of current version April 20, 2012. This paper is based on a plenary talk given at the Photonics Society Annual Meeting, 2011. The paper is dedicated to Prof. Walter R. Leeb, Technical University of Vienna, Austria, on the occasion of his 70th birthday and to Dr. Herwig Kogelnik, Bell Labs, USA, on the occasion of his 80th birthday. (e-mail: peter.winzer@bell-labs.com).

Abstract: Wavelength-division multiplexing (WDM) has been the workhorse of data networks, accommodating exponential traffic growth for two decades. Recently, however, progress in WDM capacity research has markedly slowed down as experiments are closely approaching fundamental Shannon limits of nonlinear fiber transmission. Space-division multiplexing (SDM) is expected to further scale network capacities, using parallel strands of single-mode fiber, uncoupled or coupled cores of multicore fiber, or even individual modes of few-mode fiber in combination with multiple-input–multiple-output (MIMO) digital signal processing. At the beginning of a new era in optical communications, we review initial research in SDM technologies and address some of the key challenges ahead.

Index Terms: Wavelength-division multiplexing, spatial multiplexing, space-division multiplexing (SDM).

1. Exponentially Increasing Traffic Demands and the Role of WDM

Network traffic has been growing exponentially over the past two decades, at 30 to 60% per year, depending on the nature and penetration of services offered by network operators in different geographic regions [1], [2]. The growing number of applications relying on machine-to-machine traffic and cloud computing are accelerating this growth for data-centric operators as the network is increasingly taking the role of a distributed computer interface, whose bandwidth demands are proportional to the system's processing power due to Amdahl's rule of thumb [3], and are hence evolving at close to 90% per year [4].

The demand for communication bandwidth has been economically met by wavelength-division multiplexing (WDM), researched, developed, and abundantly deployed since the early 1990s [5]. At first, WDM capacities increased at around 80% per year, predominantly through improvements in optoelectronic device technologies. By the early 2000s, lasers had reached Gigahertz frequency stabilities, optical filters had bandwidths allowing for 50-GHz WDM channel spacings, and 40-Gb/s optical signals filled up these frequency slots. At this remarkable point in time where "optical and electronic bandwidths met," optical communications had to shift from physics toward communications engineering to increase spectral efficiencies, i.e., to pack more information into the limited (~5-THz) bandwidth of optical amplifiers. Consequently, the last decade has seen a vast adoption of concepts from radio-frequency communications, such as advanced modulation formats [6], coherent detection [7], considered mostly for free-space applications over the past two decades [8], and sophisticated digital signal processing (DSP) [9]. The transition to digital coherent systems was aided by the fact that coherent detection naturally enables the exploitation of both quadratures and

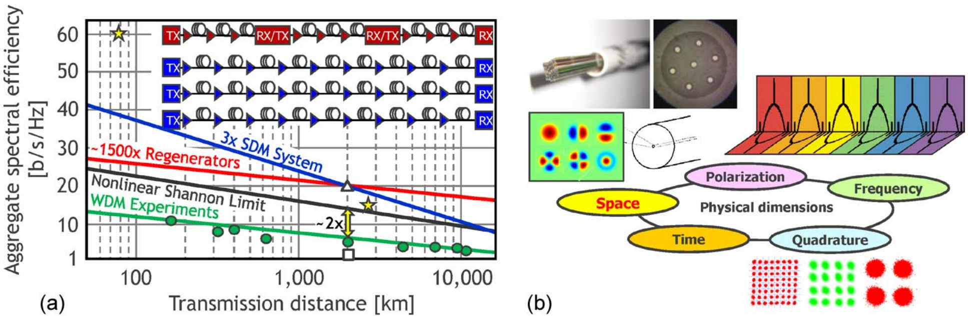

Fig. 1. (a) Tradeoff between spectral efficiency and reach of WDM experiments (green), approaching the nonlinear Shannon limit (black) to within a factor of 2. For a realistic spectral efficiency and distance target (triangle), regenerated systems (red) need about 500 times more transponders than parallel (SDM) systems (blue). (b) Today's WDM products exploit all physical dimensions but space.

polarizations of the optical field, which reduced symbol rates by a factor of 4 and brought signals within the reach of fast analog-to-digital converters (ADCs). Commercial coherent systems for fiber-optic networks were introduced at 40 and 100 Gb/s in 2008 and 2010, using polarization-division multiplexed (PDM) quadrature phase-shift keying (QPSK) at 11.5 and 28 GBaud, based on custom-designed CMOS ASICs to handle the massive required DSP functions for adaptive polarization tracking, chromatic dispersion compensation, and forward error correction (FEC).

Today's commercial WDM systems transmit close to 10 Tb/s of traffic at 100 Gb/s per wavelength. In research, interface rates of 640 Gb/s have been achieved using polarization multiplexed quadrature amplitude modulation (QAM) at a symbol rate of 80 GBaud [10]. Higher interface rates of 1 Tb/s and beyond are achieved through orthogonal frequency division multiplexed (OFDM) coherent optical superchannels [11], and the 100-Tb/s per-fiber capacity mark has recently been reached [12], [13]. However, capacities of conventional single-mode fiber systems are not expected to grow much further. Capacity increases in WDM research have slowed down from about 80% per year in the 1990s to about 20% per year since 2002, with a similar trend observed in commercial systems [1], [6]. This trend is explained by recent studies on the nonlinear Shannon capacity of optical networks [14]: Research experiments have approached their fundamental limits to within a factor of $\sim$2. This is visualized in Fig. 1(a), showing the February 2012 status of experimental WDM research spectral efficiencies (green, circles) together with the nonlinear Shannon limit [14] (black) versus transmission distance. More spectrally efficient higher-order modulation comes at the expense of reduced transmission reach due to a lower tolerance to optical amplifier noise and other signal impairments of practical importance such as laser phase noise, ADC resolution, or crosstalk. Advances in low-loss or low-nonlinearity fiber will not be able to change this picture significantly [15]. Today's commercial systems, operating at $\sim$2 b/s/Hz over $\sim$2000 km of fiber, are represented by the open square in Fig. 1(a). Assuming a 30 to 60% traffic growth per year, spectral efficiencies of 20 b/s/Hz (over the same, geography-enforced distances) will be needed in commercial systems within 5 to 10 years (open triangle), which is well beyond the Shannon limit. This observation leads to the notion of an imminent "*optical networks capacity crunch*" [16].

2. Spatial Multiplexing to Overcome the Capacity Crunch

Fig. 1(a) compares two approaches that may be taken to scale network capacities. The first option uses a concatenation of high-spectral-efficiency systems, shifting the baseline curve (green) to the right (red) by the number of regeneration spans. The scalability problem of this solution is immediately evident: With today's experimental records as a baseline, a target spectral efficiency of 20 b/s/Hz over 2000 km would require around 1500 1.3-km regeneration spans using, e.g., PDM 4096-QAM with rectangular spectral shaping and about 20% FEC overhead. In contrast, a parallel approach may be taken. This can be done using multiple optical amplification bands or, likely more scalably, multiple parallel optical paths, referred to as *spatial multiplexing* or *space-division multiplexing (SDM)*: With just 3 parallel optical paths at 7 bits/s/Hz each (e.g., using PDM 32-QAM), the desired aggregate capacity is achieved with a total of 3 transponders. The almost 3 orders of magnitude difference in transponder count between the two solutions clearly points to SDM as the preferred solution for network capacity growth [17]. Looking at Fig. 1(b), which shows the known physical dimensions that can be exploited for optical modulation and multiplexing, SDM appears to be the *only* option to significantly scale optical system capacities.

Deploying SDM in its most trivial form by using parallel optical line systems is a scalable but not yet an economically sustainable path forward, since it still does not reduce the cost or energy per bit compared with today's systems: M parallel systems carry M times the capacity at M times the cost or energy. Commercially successful SDM technologies will be expected to scale capacity with a similar per-bit cost and energy reduction as WDM ($\sim$20% per year [18]), leveraging *integration* and sharing system components among spatial and spectral channels. Integration may take place on a system and network level, on a transponder [19], [20] and DSP level, on an optical amplifier level [21], [22], and on a fiber level [23]–[25]. Since integration generally comes at the expense of *crosstalk* among parallel paths, proper crosstalk management will be an important aspect of SDM systems. In addition, SDM will have to allow for smooth system upgrades, reusing as much as possible the deployed WDM infrastructure. Initial global efforts in SDM research are reviewed in [26] and [27].

2.1. Spatial Multiplexing in the Low-Crosstalk Regime

Whether a given level of crosstalk can be treated as a system impairment or needs to be actively compensated depends on the underlying modulation format; while QPSK tolerates as much as -15 dB of crosstalk for a 1-dB signal-to-noise ratio penalty, 64-QAM tolerates only about -30 dB [28]. A key challenge associated with nominally uncoupled SDM systems will hence be to ensure sufficiently low crosstalk over long-haul, optically networked transmission distances, including integrated transponders, amplifiers, splices, connectors, SDM fibers, and network elements such as spatial and spectral crossconnects.

Recently, low-crosstalk 7-core [29], [30] and 19-core [31] fiber for SDM has been reported, and impressive system experiments have been performed, including record per-fiber capacities of 109 Tb/s [32], 112 Tb/s [29], and 305 Tb/s [31] over up to several ten kilometers, as well as Tb/s SDM transmission over 2688 km [33] and an aggregate per-fiber spectral efficiency of 60 b/s/Hz [34]. The latter two results are visualized by yellow asterisks in Fig. 1(a), well beyond the nonlinear Shannon limit for single-mode fiber.

2.2. Spatial Multiplexing With High Crosstalk and MIMO Processing

If crosstalk rises to levels where it induces unacceptable transmission penalties, *multiple-input–multiple-output (MIMO)* techniques, originally developed for wireless systems [35], can be used. If SDM transponders are able to selectively excite and coherently detect the complete orthonormal set of modes whose propagation is supported by the transmission waveguide, and if the transmission properties of each mode in terms of fiber nonlinearities and noise are comparable with those of a single-mode waveguide, a reliable M-fold capacity gain can be achieved [36]. Some of the key challenges associated with MIMO-SDM systems are the implementation of scalable coupled-mode waveguides with differential group delays small enough to be handled by MIMO-DSP, of optical amplifiers with low mode-dependent gain and noise variations, as well as of spatial and spectral crossconnects operating outside the well-defined boundaries of single-mode optics. Importantly, tradeoffs between linear and nonlinear coupled-mode optical propagation characteristics and the need for joint optoelectronic interfacing, digitizing, and MIMO processing of M high-speed signals will limit the maximum feasible number of coupled modes. Determining the right balance between coupled and uncoupled SDM transmission paths, both from an optical and from an electronic point of view, will hence be a critical consideration in the evolution of SDM technologies.

Recently, several impressive experimental demonstrations of coupled-mode MIMO-SDM transport have been reported, including up to 4200-km transmission of six spatial and polarization modes over microstructured [37] and few-mode [38] fiber, MIMO-SDM using up to 5 partially coupled spatial modes [39], and discrete [40], [41] as well as distributed Raman [42] amplification of few-mode signals.

3. Conclusions

After a decade of physics-oriented WDM research followed by a decade of applying advanced communications engineering principles to fiber-optic systems, optical transport networks research is entering the new era of spatial multiplexing, which presents a large number of interdisciplinary challenges to develop technologies that may be able to overcome the looming optical network capacity crunch.

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References

[1] R. W. Tkach, "Scaling optical communications for the next decade and beyond," *Bell Labs Tech. J.*, vol. 14, no. 4, pp. 3–9, Feb. 2010.
[2] S. K. Korotky, "Traffic trends: Drivers and measures of cost-effective and energy-efficient technologies and architectures for backbone optical networks," in *Proc. OFC/NFOEC*, Los Angeles, CA, 2012, Paper OM2G.1.
[3] J. Gray and P. Shenoy, "Rules of thumb in data engineering," Microsoft Res., Redmond, WA, Tech. Rep. MS-TR-99-100, 2000.
[4] [Online]. Available: http://top500.org/lists/2010/06/performance
[5] H. Kogelnik, "On optical communication: Reflections and perspectives," in *Proc. ECOC*, Stockholm, Sweden, 2004, Paper Mo1.1.1.
[6] P. J. Winzer, "Beyond 100G Ethernet," *IEEE Commun. Mag.*, vol. 48, no. 7, pp. 26–30, Jul. 2010.
[7] H. Sun, K. T. Wu, and K. Roberts, "Real-time measurements of a 40 Gb/s coherent system," *Opt. Exp.*, vol. 16, no. 2, pp. 873–879, Jan. 2008.
[8] W. R. Leeb, "Coherent optical space communications," in *Advanced Methods for Satellite and Deep Space Communications*, J. Hagenauer, Ed., 1992, ISBN 978-3-540-55851-4.
[9] S. J. Savory, "Digital filters for coherent optical receivers," *Opt. Exp.*, vol. 16, no. 2, pp. 804–817, Jan. 2008.
[10] G. Raybon, A. L. Adamiecki, S. Randel, C. Schmidt, P. J. Winzer, A. Konczykowska, F. Jorge, J.-Y. Dupuy, L. L. Buhl, S. Chandrasekhar, X. Liu, A. H. Gnauck, C. Scholz, and R. Delbue, "All-ETDM 80-Gbaud (640-Gb/s) PDM 16-QAM Generation and Coherent Detection," *Photon. Technol. Lett.*, 2012, submitted for publication.
[11] X. Liu and S. Chandrasekhar, "Beyond 1-Tb/s superchannel transmission," in *Proc. IEEE Photonics Conf.*, Arlington, VA, 2011, Paper ThBB1.
[12] D. Qian, M.-F. Huang, E. Ip, Y.-K. Huang, Y. Shao, J. Hu, and T. Wang, "101.7-Tb/s (370 $\times$ 294-Gb/s) PDM-128QAM-OFDM transmission over 3 $\times$ 55-km SSMF using pilot-based phase noise mitigation," in *Proc. OFC/NFOEC*, Los Angeles, CA, 2011, Paper PDPB5.
[13] A. Sano, T. Kobayashi, S. Yamanaka, A. Matsuura, H. Kawakami, Y. Miyamoto, K. Ishihara, and H. Masuda, "102.3-Tb/s (224 $\times$ 548-Gb/s) C- and extended L-band all-Raman transmission over 240 km using PDM-64QAM single carrier FDM with digital pilot tone," in *Proc. OFC/NFOEC*, Los Angeles, CA, 2012, Paper PDP5C.3.
[14] R.-J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, "Capacity limits of optical fiber networks," *J. Lightwave Technol.*, vol. 28, no. 4, pp. 662–701, Feb. 2010.
[15] R.-J. Essiambre, "Impact of fiber parameters on nonlinear fiber capacity," in *Proc. OFC/NFOEC*, Los Angeles, CA, 2011, Paper OTuJ1.
[16] A. R. Chraplyvy, "The coming capacity crunch," in *Proc. ECOC*, Vienna, Austria, 2009, plenary talk.
[17] P. J. Winzer, "Energy-efficient optical transport capacity scaling through spatial multiplexing," *IEEE Photon. Technol. Lett.*, vol. 23, no. 13, pp. 851–853, Jul. 2011.
[18] R. S. Tucker, "Green optical communications—Part I: Energy limitations in transport," *IEEE J. Sel. Topics Quantum Electron.*, vol. 17, no. 2, pp. 245–260, Mar./Apr. 2011.
[19] C. R. Doerr and T. F. Taunay, "Silicon photonics core-, wavelength-, and polarization-diversity receiver," *IEEE Photon. Technol. Lett.*, vol. 23, no. 9, pp. 597–599, May 2011.
[20] B. G. Lee, D. M. Kuchta, F. E. Doany, C. L. Schow, C. Baks, R. John, P. Pepeljugoski, T. F. Taunay, B. Zhu, M. F. Yan, G. E. Oulundsen, D. S. Vaidya, W. Luo, and N. Li, "120-Gb/s 100-m transmission in a single multicore multimode fiber containing six cores interfaced with a matching VCSEL array," in *Proc. IEEE Photonics Soc. Summer Topical Meeting*, 2010, Paper TuD4.4.

[21] P. M. Krummrich, "Optical amplification and optical filter based signal processing for cost and energy efficient spatial multiplexing," *Opt. Exp.*, vol. 19, no. 17, pp. 16 636–16 652, Aug. 2011.
[22] K. S. Abedin, T. F. Taunay, M. Fishteyn, M. F. Yan, B. Zhu, J. M. Fini, E. M. Monberg, F. V. Dimarcello, and P. W. Wisk, "Amplification and noise properties of an erbium-doped multicore fiber amplifier," *Opt. Exp.*, vol. 19, no. 17, pp. 16 715–16 721, Aug. 2011.
[23] T. Morioka, "New generation optical infrastructure technologies: EXAT initiative towards 2020 and beyond," in *Proc. OECC*, Hong Kong, 2009, Paper FT4.
[24] Y. Kokubun and M. Koshiba, "Novel multi-core fibers for mode division multiplexing: proposal and design principle," *IEICE Electron. Exp.*, vol. 6, no. 8, pp. 522–528, Apr. 2009.
[25] S. K. Korotky, "Price-points for components of multi-core fiber communication systems in backbone optical networks," *J. Opt. Netw.*, 2011, submitted for publication.
[26] G. Li and X. Liu, "Focus issue: Space multiplexed optical transmission," *Opt. Exp.*, vol. 19, no. 17, pp. 16 574–16 575, Aug. 2011.
[27] T. Morioka, Y. Awaji, R. Ryf, P. Winzer, D. Richardson, and F. Poletti, "Enhancing optical communications with brand new fibers," *IEEE Commun. Mag.*, vol. 50, no. 2, pp. s31–s42, Feb. 2012.
[28] P. J. Winzer, A. H. Gnauck, A. Konczykowska, F. Jorge, and J.-Y. Dupuy, "Penalties from in-band crosstalk for advanced optical modulation formats," in *Proc. ECOC*, Geneva, Switzerland, 2011, Paper Tu.5.B.7.
[29] B. Zhu, T. F. Taunay, M. Fishteyn, X. Liu, S. Chandrasekhar, M. F. Yan, J. M. Fini, E. M. Monberg, and F. V. Dimarcello, "112-Tb/s Space-division multiplexed DWDM transmission with 14-b/s/Hz aggregate spectral efficiency over a 76.8-km seven-core fiber," *Opt. Exp.*, vol. 19, no. 17, pp. 16 665–16 671, Aug. 2011.
[30] T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber," *Opt. Exp.*, vol. 19, no. 17, pp. 16 576–16 592, Aug. 2011.
[31] J. Sakaguchi, B. J. Puttnam, W. Klaus, Y. Awaji, N. Wada, A. Kanno, T. Kawanishi, K. Imamura, H. Inaba, K. Mukasa, R. Sugizaki, T. Kobayashi, and M. Watanabe, "19-core fiber transmission of 19 $\times$ 100 $\times$ 172-Gb/s SDM-WDM-PDM-QPSK signals at 305Tb/s," in *Proc. OFC/NFOEC*, Los Angeles, CA, 2012, Paper PDP5C.1.
[32] J. Sakaguchi, Y. Awaji, N. Wada, A. Kanno, T. Kawanishi, T. Hayashi, T. Taru, T. Kobayashi, and M. Watanabe, "109-Tb/s (7 $\times$ 97 $\times$ 172-Gb/s SDM/WDM/PDM) QPSK transmission through 16.8-km homogeneous multi-core fiber," in *Proc. OFC/NFOEC*, Los Angeles, CA, 2011, Paper PDPB6.
[33] S. Chandrasekhar, A. H. Gnauck, X. Liu, P. J. Winzer, Y. Pan, E. C. Burrows, B. Zhu, T. F. Taunay, M. Fishteyn, M. F. Yan, J. M. Fini, E. M. Monberg, and F. V. Dimarcello, "WDM/SDM transmission of 10 $\times$ 128-Gb/s PDM-QPSK over 2688-km 7-core fiber with a per-fiber net aggregate spectral-efficiency distance product of 40 320 km b/s/Hz," in *Proc. ECOC*, Geneva, Switzerland, 2011, Paper Th.13.C.4.
[34] X. Liu, S. Chandrasekhar, X. Chen, P. J. Winzer, Y. Pan, T. F. Taunay, B. Zhu, M. Fishteyn, M. F. Yan, J. M. Fini, E. M. Monberg, and F. V. Dimarcello, "1.12-Tb/s 32-QAM-OFDM superchannel with 8.6-b/s/Hz intrachannel spectral efficiency and space-division multiplexing with 60-b/s/Hz aggregate spectral efficiency," in *Proc. ECOC*, Geneva, Switzerland, 2011, Paper Th.13.B.1.
[35] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell Labs Tech. J.*, vol. 1, no. 2, pp. 41–59, Summer 1996.
[36] P. J. Winzer and G. J. Foschini, "MIMO capacities and outage probabilities in spatially multiplexed optical transport systems," *Opt. Exp.*, vol. 19, no. 17, pp. 16 680–16 696, Aug. 2011.
[37] R. Ryf, R.-J. Essiambre, A. H. Gnauck, S. Randel, M. A. Mestre, C. Schmidt, P. J. Winzer, R. Delbue, P. Pupalaikis, A. Sureka, T. Hayashi, T. Taru, and T. Sasaki, "Space-division multiplexed transmission over 4200 km 3-core microstructured fiber," in *Proc. OFC/NFOEC*, Los Angeles, CA, 2012, Paper PDP5C.2.
[38] S. Randel, R. Ryf, A. H. Gnauck, M. A. Mestre, C. Schmidt, R.-J. Essiambre, P. J. Winzer, R. Delbue, P. Pupalaikis, A. Sureka, Y. Sun, X. Jiang, and R. Lingle, "Mode-multiplexed 6 $\times$ 20-GBd QPSK transmission over 1200-km DGD-compensated few-mode fiber," in *Proc. OFC/NFOEC*, Los Angeles, CA, 2012, Paper PDP5C.5.
[39] C. Koebele, M. Salsi, L. Milord, R. Ryf, C. Bolle, P. Sillard, S. Bigo, and G. Charlet, "40 km transmission of five mode division multiplexed data streams at 100 Gb/s with low MIMO-DSP complexity," in *Proc. ECOC*, Geneva, Switzerland, 2011, Paper Th.13.C.3.
[40] Y. Yung, S. Alam, Z. Li, A. Dhar, D. Giles, I. Giles, J. Sahu, L. Gruner-Nielsen, F. Poletti, and D. J. Richardson, "First demonstration of multimode amplifier for spatial division multiplexed transmission systems," in *Proc. ECOC*, Geneva, Switzerland, 2011, Paper Th.13.K.4.
[41] E. Ip, N. Bai, Y.-K. Huang, E. Mateo, F. Yaman, M.-J. Li, S. Bickham, S. Ten, J. Linares, C. Montero, V. Moreno, X. Prieto, V. Tse, K. M. Chung, A. Lau, H.-Y. Tam, C. Lu, Y. Luo, G.-D. Peng, and G. Li, "88 $\times$ 3 $\times$ 112-Gb/s WDM transmission over 50 km of three-mode fiber with inline few-mode fiber amplifier," in *Proc. ECOC*, Geneva, Switzerland, 2011, Paper Th.13.C.2.
[42] R. Ryf, A. Sierra, R. Essiambre, S. Randel, A. H. Gnauck, C. Bolle, M. Esmaeelpour, P. J. Winzer, R. Delbue, P. Pupalaikise, A. Sureka, D. W. Peckham, A. McCurdy, and R. Lingle, "Mode-equalized distributed Raman amplification in 137-km few-mode fiber," in *Proc. ECOC*, Geneva, Switzerland, 2011, Paper Th.13.K.5.