OFC 2008
Perspectives on Optical Communications

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- Celebrate Telecom Anniversaries
- Broadband, FTTH & FTTP
- TERABITS/s and TERAMETERS
  Advanced Modulation Formats
  100 Gb/s per wavelength
  Advances in photonic integration
Acknowledgements

Andy Chraplyvy, Y. K. Chen, Chris Doerr, Rene Essiambre, Olivier Gautheron, Randy Giles, Alan Gnauck, Peter Kaiser, Steve Korotky, Richard Mack, Greg Raybon, Richard Wagner, Peter Winzer,
Happy 50th Anniversary
To Optical Communications

Three claims in first laser patent subm. 1958

2,929,922
MASERS AND MASER COMMUNICATIONS SYSTEM


Application July 30, 1958, Serial No. 752,137

11 Claims. (Cl. 250—7)
TAT 8 TRANSATLANTIC SYSTEM

6,100 km

1988

Happy Anniversary!
The first word across the Atlantic

August 16, 1858
Message from Queen Victoria to president James Buchanan

Cyrus Field, Lord Kelvin, Samuel Morse

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See: Stefan Zweig, Sternstunden der Menschheit
Today: > 500 000 km of undersea cable
Undersea cables
Asia Pacific
Global Fiber Deployment (Mkm)
courtesy: KMI Research, CRU Group

Other S-M = utility, railway, highway, government, military, premises, etc.
Other local tel. = CO trunks, metro rings, business/office parks, CLEC, etc.
Worldwide Broadband Subscribers by Technology
courtesy: KMI Research, CRU Group
Factory installed aerial cable branch and drop closure (courtesy: R. E. Wagner)
Cost of fiber vs copper

Life-Cycle Cost Savings
Accelerate Copper Parity

Most Likely New Line
(Copper Distribution)

FTTH
FTTC
FTTx deployment in North America
courtesy: R. E. Wagner

- Number of homes connected:
  - 2002: 0
  - 2003: 0
  - 2004: 0
  - 2005: 0
  - 2006: 0
  - 2007: 9

- Number of homes passed but not connected:
  - 2002: 0
  - 2003: 0
  - 2004: 0
  - 2005: 1
  - 2006: 2
  - 2007: 3

- Estimated number of homes passed or connected (millions):
  - 2002: 0
  - 2003: 0
  - 2004: 0
  - 2005: 0
  - 2006: 0
  - 2007: 9
  - 2008: 10
  - 2009: 20
  - 2010: 30
  - 2011: 40
  - 2012: 45
Global FTTx deployment

courtesy: R. E. Wagner
Bend-tolerant fiber reduces cabinet size

courtesy: R. E. Wagner
Photonic Crystal Fibers

www.bath.ac.uk/physics/

www.crystal-fibre.com

P. Kaiser et al., 1972

www.nrl.navy.mil
GLOBAL TELECOMS TRAFFIC

Year

Average network traffic [Gbit/s]

100000
10000
1000
100
10
1

World
USA
Voice
Data

Sources:
Transistor Scaling Trend

Transistor Cut-Off Frequency (GHz)

Year


Courtesy: Y.K. Chen
Amdahl’s Law: 1 MIPS networked computing power requires 1 Mbps I/O bandwidth
Commercial Lightwave System Capacity

DATA RATE per CHANNEL (Gb/s)

Data Rate:
- 10Gb/s
- 100Gb/s

Number of Channels:
- Optics
- Electronics

Ref.: '95 '96 '98 '01 '03

Total capacity:
- 100Tb/s
- 10Tb/s
- 1Tb/s
- 10Gb/s
- 100Gb/s
Integrated WDM PICs

- **100G parallel transport** (= OTN VCAT)
- Use *multiple* wavelengths & modulators

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R. Nagarajan, et. al, OFC/NFOEC, PDP32, 2007
25.6 Tb/s RZ-DQPSK Transmission on Single Fiber

A. H. Gnauck et al., Proc. OFC, 2007

9 THz @ 193 THz
5% Bandwidth

160 Wavelengths & 2x80 Gb/s per λ
Pol-Mux

50GHz/100GHz Interleaver

80 Gbit/s DQPSK

Wavelength [nm]

Relative Power (dB)

C-Band
80 channels 2 x 80 Gbit/s

L-Band
80 channels 2 x 80 Gbit/s

Spectrum [dB]

Wavelength [nm]
Advanced modulation formats

1 bit/symbol

- ~112 Gbaud
  (OOK, DB/PSBT, …)

- OOK
  Im\{E_x\} \rightarrow Re\{E_x\}

- DPSK
  Im\{E_x\} \rightarrow Re\{E_x\}

2 bits/symbol

- ~56 Gbaud
  (DQPSK, pol-muxed OOK, …)

- Im\{E_x\} \rightarrow Re\{E_x\}

4 bits/symbol

- ~28 Gbaud
  (pol-muxed (D)QPSK, 16-QAM, …)

- Im\{E_x\} \rightarrow Re\{E_x\}

- Im\{E_y\} \rightarrow Re\{E_y\}

E_x … Optical field, x-polarization
E_y … Optical field, y-polarization
Optical Spectra of Modulation Formats

- Spectra and eye diagrams have been generated through simulation tools.
- Inset of each figure shows intensity eye diagram
- The x-axis (Frequency) is normalized in terms of the bit-rate R.

P. J. Winzer and R-J. Essiambre, Optical Fiber Telecommunications V
Fiber Capacity Estimate

Capacity per unit bandwidth (spectral efficiency) for 2000-km transmission

- Signal is distorted by nonlinear transmission → there is a maximum spectral density of information that can be transmitted over optical fibers.
- For 2000 km a spectral efficiency of ~5.5 bits/s/Hz can be achieved.
- This corresponds to an increase by a factor ~10 in distance and ~3 in spectral efficiency over record experiments.

**Courtesy: Rene Essiambre**

ASK: Amplitude-shift keying, M-PSK: M-ary Phase-shift keying
NRZ-DQPSK on 100-GHz grid over 1200 km and 6 ROADM

- 1.0 Tb/s capacity (10 x 107 Gb/s)
- High spectral efficiency, 1.0 bit/s/Hz, (100-GHz channel spacing)
  - No polarization multiplexing

P. Winzer et al., OFC 2007
107 Gb/s DQPSK over Commercial LambdaXtreme® Transport system

700-km transmission w/ intermediate ROADM successfully demonstrated
- Laboratory Demonstration
- Single wavelength 100 Gb/s – Alien wavelength (compatible Optics)
- 21 other wavelengths, mix of 10 Gb/s and CW
- No changes necessary to line system or monitoring and software control

Raybon, et. al, OFC/NFOEC 2008 paper OMQ4
Note also: T. J. Xia et al., OFC 2008, NMC2, (Verizon field trial)
Monolithic InP 107-Gb/s RZ-DQPSK receiver

C. R. Doerr et al. OFC 2008
High-capacity Research Experiments

Research records

Optical Amplifier → WDM

25.6 Tb/s

Relative Power (dB)

Wavelength (nm)

System capacity

Tb/s

Gb/s

Year


53.5-Gbd DQPSK

107-Gbd OOK

10 ps
Coherent receivers in optical networking

Spectral efficiency:
- Richer symbol constellations, > 4-level
- Pol-mux

Digital signal processing:
- intradyning
- Simple impairment mitigation

C.R.S.Fludger et al., OFC, PDP22 (2007)

From [1]:

P.J.Winzer et al., LEOS Summer Topicals, 2007
OFC 2008

Outlook

**Broadband Services:** FTTH, FTTP, GbE?

- strong technical **progress**:
  - photonic integration vs increased complexity
  - advanced modulation formats
  - photonic crystal fibers, etc., etc.

- from **pt-to- pt** towards WDM **networking**
  - network security
  - packet routing