Serial PHY for Higher-Speed Ethernet

IEEE 802.3 High-Speed Study Group

September 18-21, 2006

- **Marcus Duelk**
  Bell Labs / Lucent Technologies
  duelk@lucent.com
- **Stephen Trowbridge**
  Lucent Technologies
  sjtrowbridge@lucent.com

Lucent Technologies
Bell Labs Innovations

Outline

- Motivation
- Applications & Markets
- Economic Benefits for WDM Networks
  - Higher spectral density & capacity → lower cost per bit
  - Fewer management issues & lower costs
- Technical Feasibility
  - Optical transmission demonstrations
  - PMA and PMD device demonstrations
  - Transmission reach
  - Modulation format examples

Motivation

- Historically parallel PHYs using wavelength- or space-division multiplexing have been used if
  - the transmission channel does not provide a sufficient bandwidth-distance product (e.g. twisted-pair electrical cables, multi-mode optical fibers)
  - the technology for serial PHY is not mature enough and/or not cost-effective
- Historically serial PHYs have replaced parallel PHYs as technology matured
- We propose to consider the serial PHY for Higher-Speed Ethernet ...

Application & Markets

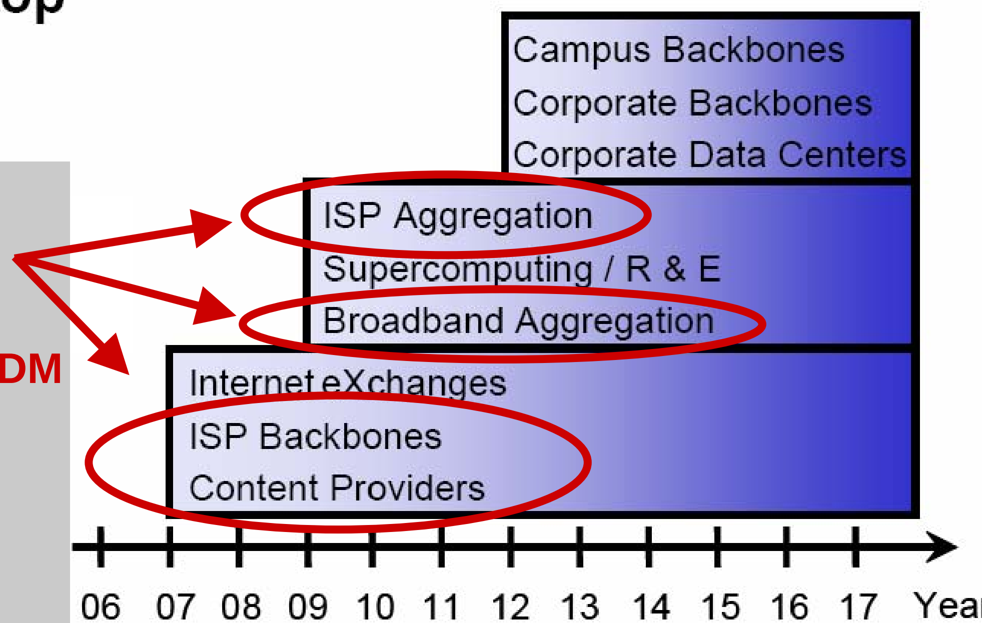
- Bird's eye view
  - Not targeted at the desktop
  - Multiple applications throughout the network

• Most (first) applications of higher-speed Ethernet are found in provider networks in the MAN/WAN space

• Most MANs/WANs backbones are WDM systems with optical amplification

• "All data on a single wavelength" (serial PHY) has some benefits for WDM networks ...

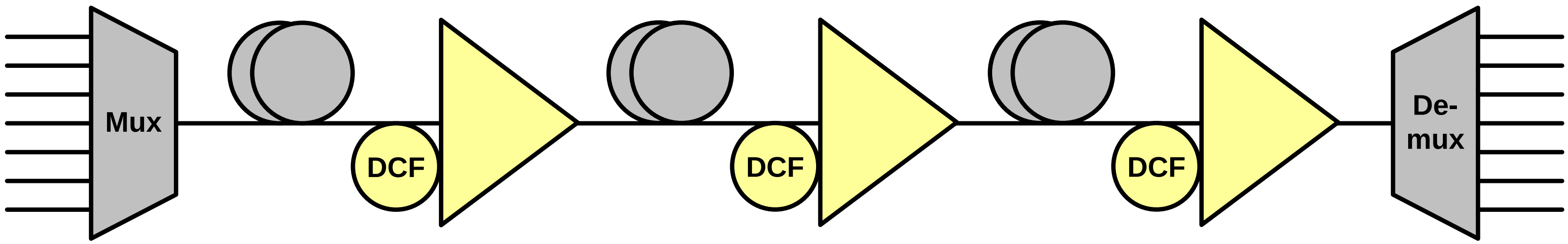
• Spectral density and total capacity important (relates to $$$/bit)
→ benefits with serial PHY



Market Adopters

  - Possibility of > 1 project
  - Study group may find multiple projects to initiate

Spectral Density & Total Capacity



- WDM MAN/WAN Link with Optical Elements (e.g. Optical Amplifiers, Dispersion Compensating Modules, Filters, etc.):
  - **Costs for optical line components shared by multiple wavelengths → add more channels to lower costs per channel**
  - **Costs per bit decreases as total capacity increases**
  - **Optical amplifiers have limited spectral window of amplification → increase spectral efficiency to squeeze in more channels**
- These "rules of economics" do not apply for short-reach systems or O-E-O repeater systems

Lucent Technologies
Bell Labs Innovations

Spectral Density

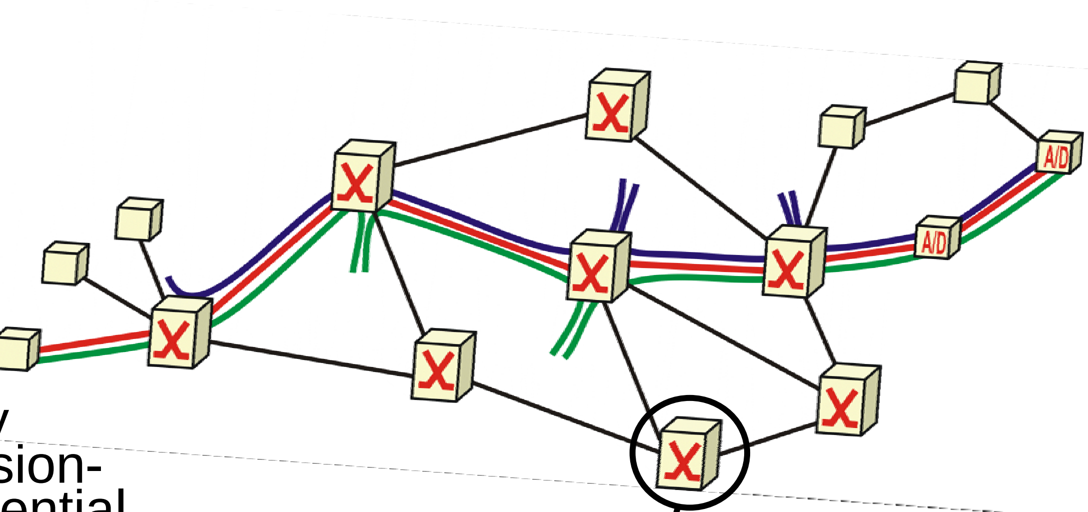
- Higher **serial** speed typically results in higher spectral efficiency (and hence higher total capacity and lower cost/bit):
  - 10 Gb/s with 50 GHz channel spacing
    → 0.2 b/s/Hz spectral efficiency
  - 40 Gb/s with 100 GHz channel spacing
    → 0.4 b/s/Hz spectral efficiency
  - 100 Gb/s with 100 GHz channel spacing*
    → 1.0 b/s/Hz spectral efficiency
- Comparison to Integrated 10 x 10Gb/s Tx device for 100G **parallel PHY** [26]:
  - 200 GHz channel spacing**
    → 0.05 b/s/Hz spectral efficiency
  - 1800 GHz span for 10 channels
    → **14.5 nm** for one 100G channel

*** e.g. using DQPSK modulation with 50 Gbaud line rate !**
**** several devices could be interleaved with external interleavers**

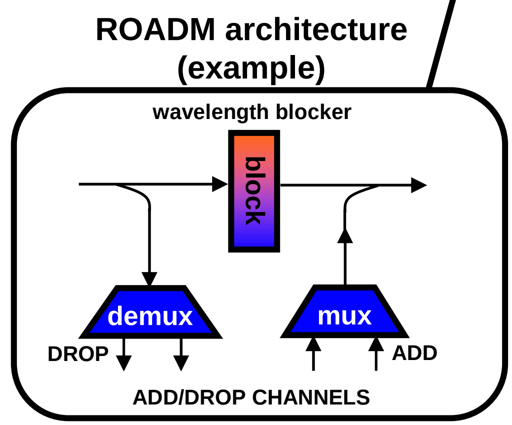
Lucent Technologies
Bell Labs Innovations

Optical Switching & ROADMs

- Provisioning, Routing, Reconfiguration on the Optical Layer using λ-selective Switches/ROADMs



- Parallel PHY solutions may experience not only dispersion-related skew but also differential delay due to path diversity
- Parallel PHY solutions may also suffer from loss, distortion, or interference on some (but not all) of the channels
- Serial PHY solutions may reduce cabling and wavelength management, lower OPEX
- Serial PHY solutions need to be backward compatible with existing filters/ROADMs



ROADM =
Reconfigurable
Optical
Add
Drop
Multiplexer

Lucent Technologies
Bell Labs Innovations

Technical Feasibility

- Technical Feasibility of the serial PHY for bit rates up to 107 Gb/s has been demonstrated
  - **Research Demonstrations:**
    - 40 Gb/s (WDM) transmission systems since 1999 [1-3]
    - 80/85 Gb/s (WDM) transmission systems in 2005/2006 [4-7]
    - 100/107 Gb/s (WDM) transmission systems in 2005/2006 [8-14]

    (all data for ETDM systems, higher rates already demonstrated using OTDM, same rates demonstrated earlier using OTDM)
  - **Commercial Availability:**
    - 40 Gb/s BER Testers since 2001
    - 40 Gb/s WDM transmission system since 2002/2003
    - 40G PoS cards with serial PHY on core routers since 2004
    - 100 Gb/s BER Testers since 2006

ETDM : Electrical Time-Division Multiplexing
OTDM : Optical Time-Division Multiplexing

100G Serial PHY is Technically Feasible

- Various 100G Serial Optical Transmission Experiments:
  - 107 Gb/s NRZ, Duobinary and DQPSK Transmission, 1000 & 2000 km (Bell Labs 2005/2006 [8,9,13,14])
  - 100 Gb/s DQPSK Transmission (KDDI, 2006 [12])
  - 107 Gb/s NRZ (Siemens/HHI, 2006 [10,11])
- 100G PMA/PMD Components:
  - 100+ Gb/s Electrical Data Receiver (Micram, 2006 [10,11,17])
  - 100+ Gb/s SERDES in SiGe (IBM, 2004 [18])
  - 100+ Gb/s SERDES in InP (NTT, 2004 [19,20], Chalmers, 2005/2006 [21,22])
  - 120 GHz photodiodes (HHI, 2005 [23])
  - 80 Gb/s modulators (KTH, 2005 [4,24], HHI, 2006 [25])

100 Gb/s (serial) BER Tester
Agilent, introduced OFC 2006

Transmission Reach

Line rate	Reach
43 Gb/s	10,000 km (demonstrated [16], ETDM)
85 Gb/s	2,000 km (demonstrated [7], ETDM)
107 Gb/s	2,000 km (demonstrated [14], ETDM)
170 Gb/s	2,000 km (demonstrated [15], OTDM)

- 2,000 km satisfies reach requirements of majority of networks
- Reach given for BER 2E-3 (Limit for enhanced FEC to correct to BER values <1E-15)
- Reach determined by nonlinear inter- and intra-channel effects, fiber type, dispersion map, modulation format, amplifier spacing, etc.

Lucent Technologies
Bell Labs Innovations

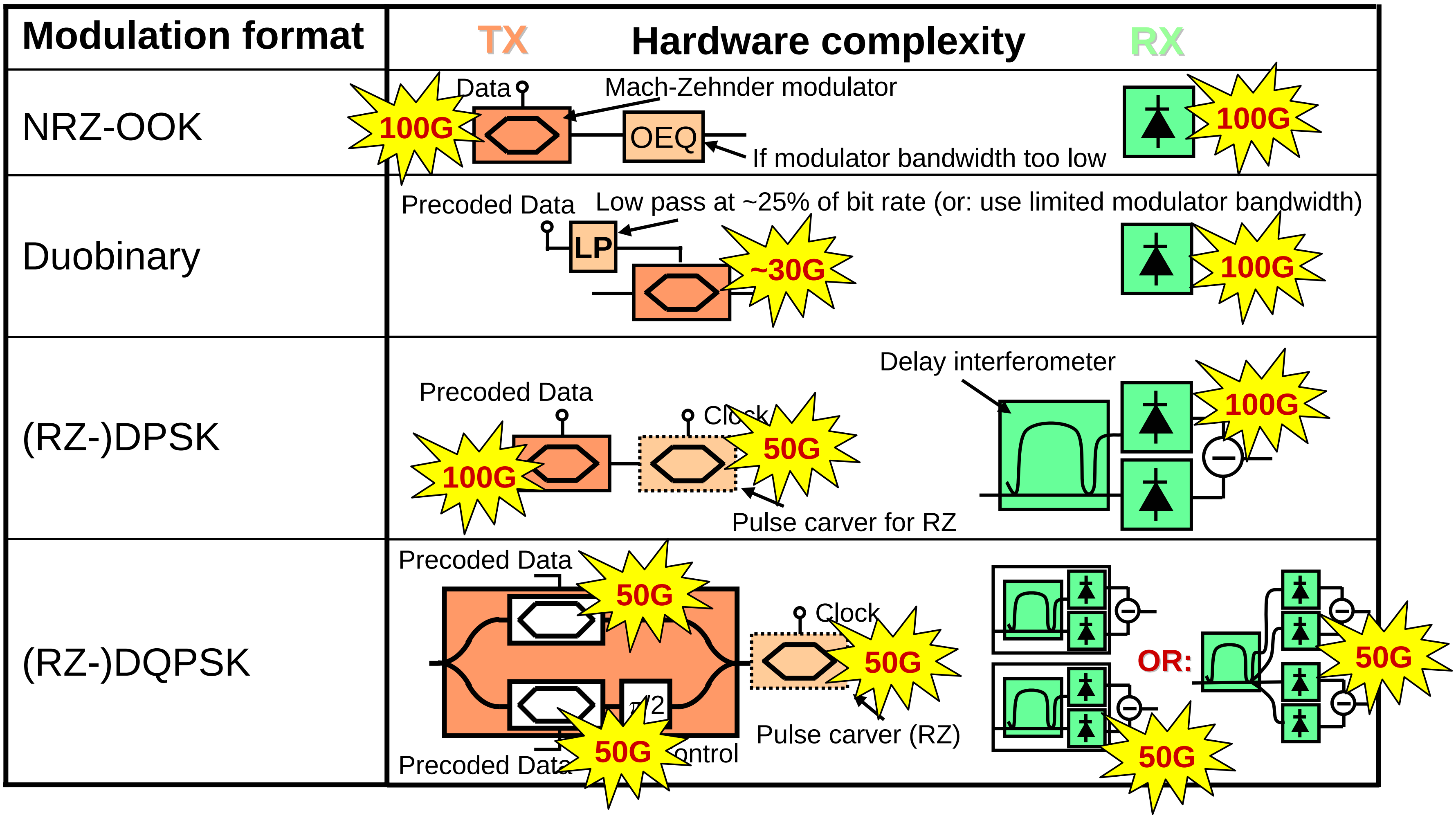
Modulation Format Examples for 100G Serial

	NRZ	Duobinary	DQPSK
Bits per Symbol	1	1	2
Line Rate (speed of electronics)	100 Gb/s	100 Gb/s	50 Gbaud
SERDES	SiGe / InP	SiGe / InP	SiGe
Spectral Efficiency	~0.7 b/s/Hz	~0.7 b/s/Hz	≥1.0 b/s/Hz
Required OSNR (BER 1E-3)	~ 21 dB	~ 24 dB	~ 19 dB
PMD tolerance (1-dB penalty)	~ 3 ps	~ 3 ps	~ 8 ps
CD tolerance (2-dB penalty)	± 8 ps/nm	± 25 ps/nm	± 26 ps/nm

- DQPSK = Differential Quadrature Phase-Shift Keying
- "100G DQPSK = 40G with 25% speed-up"
  → reuse 40G technology (optical PMD, SERDES, drivers, etc.)
  → similar cost structure as 40G but 2.5-times more throughput !

PMD Devices for 100G Serial PHY

100G (serial) DQPSK requires only
50G Electrical & Optical Components !



Conclusion

- We propose to consider serial PHYs (all data on a single optical wavelength) for Higher-Speed Ethernet
- We see benefits for WDM networks
  - higher spectral efficiency, higher total capacity
  - lower costs per bit
  - fewer wavelengths to manage, more robust
- High-Speed Serial PHY is technically feasible
  - Commercial 40G systems available for a couple of years
  - Research demonstrations at 80G+ and 100G+
  - The right choice of the modulation format may significantly reduce the challenges and requirements for PMA/PMD devices → Example: 100G DQPSK = 50 Gbaud !

Backup

Lucent Technologies
Bell Labs Innovations

References (1)

- [1] S. Kuwano et al. (NTT), OFC ’96, paper PD25-2,
  40 Gb/s ETDM transmitter WDM transmission
- [2] J.P. Elbers et al. (Siemens), ECOC ’99, paper PD2-5,
  40 Gb/s ETDM transmitter/receiver with WDM transmission, 300km
- [3] T.N. Nielsen et al. (Bell Labs), ECOC ’99, paper PD2-2,
  40 Gb/s ETDM transmitter/receiver with WDM transmission, 400km
- [4] Y. Yichuan et al. (Kista), OFC 2005, paper OWE1,
  80 Gb/s ETDM transmitter
- [5] K. Schuh et al. (Alcatel), ECOC 2005, PD paper Th4.1.4,
  80 Gb/s ETDM transmitter/receiver, single-wavelength transmission, 400km
- [6] N. Yoshikane et al. (KDDI), OFC 2004, paper PDP38,
  85 Gb/s DQPSK WDM transmission, 300km
- [7] S. Weisser et al. (Lucent), ECOC 2006, paper Mo3.2.4,
  85 Gb/s DQPSK WDM transmission, 2000km
- [8] P.J. Winzer et al. (Bell Labs), ECOC 2005, PD paper Th4.1.1.,
  107 Gb/s ETDM duobinary transmitter
- [9] C.R. Doerr et al. (Bell Labs), ECOC 2005, PD paper Th4.2.1,
  107 Gb/s ETDM NRZ transmitter
- [10] R.H. Derksen et al. (Siemens), OFC 2006, paper PDP37,
  100 Gb/s ETDM receiver, single-wavelength NRZ transmission, 480km
- [11] C. Schubert et al. (HHI), ECOC 2006, paper Tu1.5.5,
  107 Gb/s ETDM receiver, single-wavelength NRZ transmission, 480km
- [12] M. Daikoku et al. (KDDI), OFC 2006, paper PDP36,
  100 Gb/s DQPSK transmitter/receiver, single-wavelength transmission, 50km
- [13] P.J. Winzer et al. (Bell Labs), ECOC 2006, paper Tu1.5.1,
  107 Gb/s ETDM NRZ WDM transmission, 1000km
- [14] P.J. Winzer et al. (Bell Labs), ECOC 2006, submitted as PD paper,
  107 Gb/s DQPSK WDM transmission, 2000km

Lucent Technologies
Bell Labs Innovations

References (2)

- [15] A.H. Gnauck et al. (Bell Labs), IEEE Photonics Technology Letters, 2003, vol. 15, no. 11, 170 Gb/s OTDM WDM transmission, 2000km
- [16] C. Rasmussen et al. (Mintera), OFC 2003, paper PD18, 43 Gb/s ETDM transmitter/receiver with WDM transmission, 10,000km
- [17] U. Duemler et al. (Micram), IEE Electronics Letter, 2006, vol. 42, no. 1, 86 Gb/s+ electrical receiver module
- [18] M. Meghelli (IBM), IEEE Journal of Solid-State Circuits, 2004, vol. 39, no. 12, 132 Gb/s 4:1 mux realized in 0.13 μm SiGe
- [19] K. Murata et al. (NTT), IEEE Journal of Solid-State Circuits, 2004, vol. 39, no. 1, 100 Gb/s mux/demux realized in 0.10 μm InP HEMT
- [20] Y. Suzuki et al. (NTT), IEEE Journal of Solid-State Circuits, 2004, vol. 39, no. 12, 120 Gb/s mux and 110 Gb/s demux realized in InP HBT
- [21] J. Hallin et al. (Chalmers), IEEE CSIC '05, 165 Gb/s 4:1 mux realized in Vitesse's VIP2 InP DHBT process
- [22] T. Swahn et al. (Chalmers), IEEE IPRM 2006, paper MB2.1 100+ Gb/s ICs realized in Vitesse's VIP2 InP DHBT process
- [23] A. Beling et al. (HHI), IEEE Photonics Technology Letters, 2005, vol. 17, no. 10, waveguide photodiodes with 120GHz bandwidth and 0.5 A/W responsivity
- [24] U. Westergren et al. (KTH), ECOC 2004, paper Tu3.1.3, travelling-wave EAMs for 80 Gb/s
- [25] H.N. Klein et al. (HHI), IPRM 2006, paper TuA2.4, InP Mach-Zehnder modulator for 80 Gb/s
- [26] R. Nagarajan et al. (Infinera), IEEE Journal of Selected Topics in Quantum Electronics, 2005, vol. 11, no. 1, InP Photonic Integrated Circuit (PIC) devices, 10-channel transmitter/receiver at 10 Gb/s

Lucent Technologies
Bell Labs Innovations

Dispersion Tolerance

Line rate	Chromatic Dispersion Tolerance (1dB penalty)
10 Gb/s	~900 ps/nm for NRZ (±50 km SSMF)
40 Gb/s	~56 ps/nm for NRZ (±3.3 km SSMF)
80 Gb/s	~14 ps/nm for NRZ (±0.8 km SSMF)
100 Gb/s	~9 ps/nm for NRZ (±0.5 km SSMF)

- 80/100 Gb/s serial PY will require dynamic (tunable) compensators for chromatic dispersion (TDC)
- TDCs are used today in long-haul 40 Gb/s transmission systems
- TDCs for 80/100 Gb/s transmission systems may require slightly higher tuning range compared to 40G TDCs

Lucent Technologies
Bell Labs Innovations