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Application Driven Petabit Optical Networking

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Outline

• Background
• Optical Networks - State-of-the-Art
  - SDH/SONET
  - Wavelength Division Multiplexing (WDM)
  - Gigabit Ethernet (GbE)
• Optical Time Division Multiplexing (OTDM)
• ADAPTNet
• Conclusions
Background
Drivers

- network traffic will escalate dramatically to support multi-Zettabytes of data annually by 2015 (multi-million million billion bytes)
  - consumer applications
    - YouTube, IPTV, high-definition images, HDTV
    - 3D games, virtual worlds and photorealistic tele-presence
    - cloud computing
  - specialized applications
    - e-Science
    - shared instrumentation infrastructures and large remote sensors
    - content distribution
    - grid computing
    - ultra-high resolution media distribution
New Wave of Applications

A. Lightweight users, browsing, mailing, home use
B. Business applications, multicast, streaming, VPN's,
C. Scientific applications, distributed data processing/storage, all sorts of grids/clouds. Need very fat lambdas, limited multiple Virtual Organizations, few to few,

ΣA ≈ 40 Gb/s
ΣB ≈ 100 Gb/s
ΣC >> 1 Tb/s

Source: de Laat, University of Amsterdam
Network Layers

Optical Fibre Only

Fibre + Wireless
Optical Networks: State-of-the-Art
Transmission Medium; Optical Fibre

The diagram illustrates the waveforms and characteristics of optical fibres, including dispersion and attenuation properties at different wavelengths. Key points include:

- **2nd window**: 1310 nm, 15 THz (85 nm), A<0.35 dB/km
- **3rd window**: 1550 nm, 15 THz (120 nm), A<0.2 dB/km

The diagram also shows the comparison between different fibre types and amplifier technologies, such as FRA, FBA, TWA, and EDFA.
Optical Networking: Transparency

- allows format independence
  - flexibility for new traffic types
- minimizes the equipment in the signal path
  - cost advantage
**TDM/WDM**

- **Time Division Multiplexing (TDM)**

- **Wavelength Division Multiplexing (WDM)**
Capacity Upgrades

Fibre aggregate capacity

- Spectral Window
  - Transmission Fibre 100nm
  - Er3+ Doped Fibre Amplifier 32nm
  - New Amplifiers

- TDM
  - 10Gbit/s
  - 40Gbit/s
  - Higher rates

- WDM
  - 200GHz
  - 100GHz Denser grids

Fibre window
- 1500 nm to 1600 nm
- 13THz

Fibre window
- 1280 nm to 1320 nm
- 7THz

EDFA window
- 1530 nm to 1560 nm
- 4THz

Extended EDFA
- 1530 nm to 1600 nm
- 9THz
History

140Mbit/s - 2.5Gbit/s
- InP Lasers / Detectors

2.5Gbit/s - 10Gbit/s
- Er3+ Fibre Optical Amplifier

Bi-directional WDM
2-4xOC48, 2-4xOC192
5Gbit/s - 20Gbit/s
- Coarse WDM - Filters

Uni- and Bi-directional D-WDM
16xOC48, 16xOC192
40Gbit/s - 160Gbit/s
- Precision Sources - Precision Mux/Demux - ITU grid
SONET/SDH; History

- **Synchronous Optical Network - SONET**
  - North American Standard (ANSI)

- **Synchronous Digital Hierarchy - SDH**
  - International Telecommunications Union (ITU)
  - SONET, Synchronous Transport Signal, STS1 = 51.84 Mb/s
  - SDH, Synchronous Transport Module, STM1 = 155.52 Mb/s
  - Optical Carrier
    - OC3 = 3 x STS 1 = STM 1 = 155.52Mbit/s
    - OC12 = 12 x STS 1 = STM 4 = 622.08Mbit/s
    - OC48 = 48 x STS 1 = STM 16 = 2.488Gbit/s
    - OC192 = 192 x STS 1 = STM 64 = 9.953Gbit/s
    - OC768 = 768 x STS 1 = STM 256 = 39.813Gbit/s
Optical Amplifier/WDM Revolution

Repeater without optical amplifier

Repeater with optical amplifier

All optical network

Repeater

Receiver

Transmitter

S

S

Rx

Tx

Rx

Tx

Rx

Tx

Rx

Tx
Optical Amplifier/WDM Revolution

Conventional Transmission - 10Gbit/s

Optical Amplifiers and WDM - 10 Gb/s

4 fibers → 1 fiber; 12 regenerators → 1 optical amplifier

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Technology Issues:
Next Generation WDM systems

- Closer channel spacing
- More channels
  - Improved optical amplifiers
    - tighter power (pump lasers)
    - wider bandwidth
- Higher speeds (40 Gb/s)
  - Dispersion compensation
    - in amplifiers?
Simpler Layered Model

Service Layers (IP, Ethernet, ...)

Open OC-48 (2.5 Gb/s)

Proprietary (20-40 Gb/s)

Optical Layer

Media Layer
Optical Layer: 
**Format-Independent Platform**

- direct interconnection of IP or Ethernet or …
- allow provisioning and restoration to be removed from the data networking layer
- provide a flexible infrastructure for packet-based networks while still supporting legacy e.g. SONET formats
- optical network expansion beyond WDM
  - higher bitrates per wavelength through optical time division multiplexing (OTDM)
  - optical networks supporting burst or packet based transmission
Ethernet; History

- developed at Xerox from 1973-1975, widely used since 1980
- largely replaced other LAN standards by “leapfrogging” competing developments such as Token ring, FDDI etc.
- originally based on CSMA/CD protocol broadcasting over a shared coaxial cable at 10Mbit/s
  - uses globally unique 48bit Ethernet interface addresses
  - fits into data link layer of OSI model (layer 2)
- later versions developed using twisted-pair cable with RJ45 connectors or optical fibre
  - 100Mbit/s Ethernet (Fast Ethernet)
  - 1Gbit/s Ethernet (Gigabit Ethernet)
  - 10Gbit/s and 100Gbit/s versions do not use CSMA/CD
    - point-to-point operation only, interconnecting Ethernet switches
    - CSMA/CD is inefficient for high data rates
- all versions of Ethernet are based on the original 10Mbit/s frame format
- recently, “Carrier class” extensions to the protocol have been developed so that Ethernet can be used as a cost-effective replacement for SDH
10G and 100G Ethernet

• 10Gbit/s Ethernet provides point-to-point connectivity between Ethernet switches, with CSMA/CD disabled
  - standardised as IEEE 802.3ae in 2002
  - LAN PHY – most common implementation, supporting existing Ethernet LAN applications; 2 × optical fibres, multimode (300 m) or single mode (10km)
  - WAN PHY – allows 10Gbit/s Ethernet terminals to be connected through 10Gbit/s SDH/SONET; 2 × single-mode optical fibres, up to 40km
  - Both LAN PHY and WAN PHY can use the same optics
  - Twisted pair operation also available over shorter distances
• 100Gbit/s Ethernet standard (IEEE 802.3ba) is due to be approved in June 2010; operation over
  • at least 40km on single-mode fibre (4 wavelengths carrying 25Gbit/s each)
  • at least 100m on multi-mode fibre
  • at least 10m on copper cable
  - a 100Gbit/s prototype Ethernet switch was demonstrated by Nortel in 2008
SONET/Ethernet Converge
Lightwave Technology Eras

Year


Capacity (Gb)

10000
1000
100
10
1
0.1

Fiberization
Digitization

Research Systems

Commercial Systems

Multi-wavelength transmission to meet capacity requirements

SONET

Optical networking for increased functionality

Optical Internetworking

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Optical Time Division Multiplexing (OTDM)
Bandwidth Bottleneck?

- 10Tbit/s
- 100Gbit/s
- 10Gbit/s
- 1Gbit/s
- 100GE (100Gb/s)
- OC-192 (40Gb/s)
- OC-768 (100Gb/s)
- OC-48 (2.5Gb/s)
- OC-12
- OC-3
- OC-1

Limit of Current Electronic Switching

All-optical Approach

Commercial Systems (Single Channel data rates)

OTDM
OTDM

Tx-1  →  TDL
Tx-2  →  TDL
Tx-N  →  TDL

N × 1  →  1 × N

Rx-1  →  DeMux
Rx-2  →  DeMux
Rx-N  →  DeMux

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OTDM

Tx-1 → TDL
Tx-2 → TDL
Tx-N → TDL

N x 1

1 x N

Rx-1
Rx-2
Rx-N

DeMux

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OTDM

Tx-1 → TDL → N x 1 → 1 x N → Rx-1
Tx-2 → TDL → N x 1 → 1 x N → Rx-2
Tx-N → TDL → N x 1 → 1 x N → Rx-N

DeMux

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MANCHESTER 1824
OTDM

Tx-1 → TDL
Tx-2 → TDL
Tx-N → TDL

N X 1

1 x N

DeMux

Rx-1
DeMux

Rx-2
DeMux

Rx-N
OTDM

Tx-1 → TDL
Tx-2 → TDL
Tx-N → TDL

N x 1

1 x N

Rx-1
Rx-2
Rx-N
OTDM

Tx-1 → TDL → N X 1 → 1 x N → Rx-1
Tx-2 → TDL → N X 1 → 1 x N → Rx-2
Tx-N → TDL → N X 1 → 1 x N → Rx-N

DeMux

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MANCHESTER 1824
OTDM

Tx-1 → TDL
Tx-2 → TDL
Tx-N → TDL

TDL → NX1 → 1xN

DeMux

Rx-1 → DeMux
Rx-2 → DeMux
Rx-N → DeMux
OTDM

TxD-1 → TDL

TxD-2 → TDL

TxD-N → TDL

N x 1 → Demux → 1 x N

Rx-1

Rx-2

Rx-N
OTDM

Tx-1 → TDL
Tx-2 → TDL
Tx-N → TDL

N x 1 → 1 x N

Rx-1 → DeMux
Rx-2 → DeMux
Rx-N → DeMux
OTDM
OTDM

Tx-1 → TDL
Tx-2 → TDL
Tx-N → TDL

N x 1

1 x N

Rx-1
DeMux
N 2 1

Rx-2
DeMux
N 2 1

Rx-N
DeMux
N 2 1

OTDM

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OTDM; Transmitter

Transmitting to Channel 2

Time Slot Control Signals

<table>
<thead>
<tr>
<th>Tx 2</th>
<th>Time Slot Control Signals</th>
<th>RF Data</th>
<th>Transmit to Time Slot #2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 0 1</td>
<td></td>
</tr>
</tbody>
</table>

ps Pulsed Laser → Data Modulator → Time Slot Tuner → To Nx1 Combiner

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OTDM; Transmitter

Transmitting to Channel 2

- **ps Pulsed Laser**
- **Data Modulator**
- **Time Slot Tuner**
- **Tx 2**
- **Time Slot Control Signals**
- **RF Data**
- **Transmit to Time Slot #2**

To Nx1 Combiner
OTDM; Transmitter

Transmitting to Channel 2

Tx 2

Time Slot Control Signals

RF Data

Transmit to Time Slot #2

RZ Format

ps Pulsed Laser

Data Modulator

Time Slot Tuner

To Nx1 Combiner

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OTDM; Transmitter

Transmitting to Channel 2

- **Tx 2**
  - Time Slot Control Signals
  - RF Data

- **ps Pulsed Laser**
  - Data Modulator
  - Time Slot Tuner

- **Transmit to Time Slot #2**
  - RZ Format

- **To Nx1 Combiner**
OTDM; Transmitter

Transmitting to Channel 2

Ps Pulsed Laser
Data Modulator
Time Slot Tuner

Tx 2

Time Slot Control Signals
RF Data

Transmit to Time Slot #2

RZ Format

TO Nx1 Combiner
OTDM; Transmitter

Transmitting to Channel 2

Ps Pulsed Laser -> Data Modulator -> Time Slot Tuner

Time Slot Control Signals
RF Data

Transmit to Time Slot #2

RZ Format

To Nx1 Combiner

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OTDM; Transmitter

Transmitting to Channel 2

- **Pulsed Laser**
- **Data Modulator**
- **Time Slot Tuner**

Time Slot Control Signals

RF Data

Transmit to Time Slot #2

RZ Format

- **Tx 2**
- **To Nx1 Combiner**
OTDM; Self Clocked Receiver

Demultiplexing data from Channel 2

Aggregate Data

Clock & Data Separation

Time Slot Tuner

Tb/s All Optical Switch

Demuxed Data channel 2

Time-Shifted Clock
OTDM; Self Clocked Receiver

Demultiplexing data from Channel 2

Data

Aggregate Data

Clock & Data Separation

Time Slot Tuner

T

Tb/s All Optical Switch

Demultiplexed Data channel 2
OTDM; Self Clocked Receiver

Demultiplexing data from Channel 2

Aggregate Data

Clock & Data Separation

Time Slot Tuner

Data

Time-Shifted Clock

Tb/s All Optical Switch

Demultiplexed Data channel 2
OTDM; Self Clocked Receiver

Demultiplexing data from Channel 2

Clock & Data Separation

Time Slot Tuner

Data

Time-Shifted Clock

Tb/s All Optical Switch

Demultiplexed Data channel 2
Demultiplexing data from Channel 2

- **Aggregate Data**
- **Clock & Data Separation**
- **Time Slot Tuner**
- **Data**
- **Time-Shifted Clock**
- **Tb/s All Optical Switch**
- **Demultiplexed Data channel 2**

OTDM; Self Clocked Receiver
OTDM; Self Clocked Receiver

Demultiplexing data from Channel 2

Clock & Data Separation

Time Slot Tuner

Tb/s All Optical Switch

Demultiplexed Data channel 2
OTDM; Self Clocked Receiver

Demultiplexing data from Channel 2

Clock & Data Separation

Time Slot Tuner

Tb/s All Optical Switch

Demultiplexed Data channel 2
OTDM; Self Clocked Receiver

Demultiplexing data from Channel 2

Aggregated Data → Clock & Data Separation → Time Slot Tuner → Time-Shifted Clock → Tb/s All Optical Switch → Demultiplexed Data channel 2
OTDM; Self Clocked Receiver

Demultiplexing data from Channel 2

Clock & Data Separation

Aggregated Data

Time Slot Tuner

Data

Time-Shifted Clock

Tb/s All Optical Switch

Demultiplexed Data channel 2
ADAPTNet
ADAPTNet

**Physical Layer (Transmission)**

**Routing**

**Signalling**

**Discovery**

**Service Plane (Application)**

**Application Connectivity Management**

**Resource Allocation, Scheduling, QoS**

**Application Interface Network Management**

**Network Control**

User

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Solution

- multi and cross-layer solution
  - physical layer
    - >100GBit/s per channel and >1TBit/s per fibre
  - control and management plane
    - understanding of application requirements and on-demand/dynamic
  - application to network interface
    - hide network complexity and connectivity provisioning process
Solution

- Carrier Class Ethernet
  - Ethernet standard for data rates higher than 10Gbit/s is already the subject of intensive development
  - 40Gbit/s and 100Gbit/s Ethernet Task Force (ETF)
  - pre-standards equipment being available commercially in 2009

- 100Gbit/s Ethernet will provide an off-the-shelf solution in the future
  - consumer based i.e. HDTV, SHDTV

- Other applications require higher data rates and support demanding quality of service (QoS) levels
  - E-science e.g. radio astronomy, UHD multimedia
  - research is already under way on Ethernet operating at 640Gbit/s which will doubtless become the focus of future standardization activities

- Ethernet is inherently packet-based, while high performance applications
OTDM

- circuit-switched OTDM approach can adapt naturally to high-end application requirements for flexible capacity and QoS

- OTDM can offer an extra dimension to capacity upgrades
  - utilising the time dimension in the optical domain for capacity upgrades reduces the transponder complexity
  - proven ability to scale to ever higher single-channel data rates for serial ultrahigh capacity transport

- main drivers for migrating to higher single channel rates are
  - better utilization of the optical fibre
  - conservation of router ports and lowering of the network management overhead
  - factors will continue to drive the bit rate per channel higher to many 100’s of Gbit/s
Service Provisioning

- applications to set up their own virtual network in an on-demand manner
- efficient and on-demand bandwidth provisioning mechanism
- network resource virtualization mechanism that decouples service delivery from bandwidth and protocol engineering
- protocols for point-to-point, point-to-multipoint and multipoint-to-point operation
New Networking Paradigm

Application requirements
End-user requirements
Service requirements

Service Plane
Control Plane
Network Elements

• Application requirements
• End-user requirements
• Service requirements

User
WDM-OTDM
Network Elements

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Engineering
Conclusions; Network Requirements

• a dynamic ultra high-speed platform that serves different types of bandwidth intensive application seamlessly
• scalability; a solution beyond the current or emerging Ethernet and other optical transport developments
• supports the granularity requirements of individual applications
• supports end-to-end quality of service performance requirements for different types of applications
• offers application perceived network dynamics without necessarily requiring a fully dynamic optical layer; this function will be provided by the service plane
• maintains compatibility with other mainstream solutions e.g. Ethernet
• capable of deploying new applications quickly and efficiently, presenting minimal complexity to the user