All Optical Time Division Multiplexing - An alternative to WDM

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OCRG - Current Research

- All Optical Time Division Multiplexing
  - Terahertz Optical Asymmetric Demultiplexers
  - Optical Buffering
  - Optical Packet Networking
  - Optical Routing

- Optical Wireless Communication System
  - Modulation Schemes
  - CDMA
  - Intelligent Optical Receiver

- Optical Sensors
Our Work

- System approach
  - Theoretical Investigation
  - Simulation
    - Analytical
    - Computer
  - Design
  - Implementation
All Optical Time Division Multiplexing

an overview
All Optical Networks Layered Structure

To overcome the bandwidth bottleneck due to opto-electronic or electro-optic conversion in existing network based on optical transmission and electronic switching
Network Technologies

Electrical

Optical

Control signal
All Optical Multiplexing

Is the key in meeting the explosive bandwidth requirement of future communication networks!

- Wavelength division multiplexing (WDM)
- Optical time division multiplexing (OTDM)
- Hybrid WDM-OTDM
WDM

- Up to 90 wavelengths
- > 200 Gbps
- Transparent to data format and rate
Problems with WDM

- Nonlinearity associated with fibre, eg. *Stimulated Raman Scattering* results in SNR degradation as the number of channel increases
- Four wave mixing: *limits the channel spacing*
- Cross phase modulation: *limits the number of channels*
- High gain flat amplifiers
- Packet switched service by means of light paths: *an extremely inefficient way of utilizing network resources*

Solution

- **Optical Time Division Multiplexing (OTDM)**
  (introduced early 90’s)
OTDM – *What does it offer?*

- Flexible bandwidth on demand at burst rates of 100 Gb/s per wavelength (in the longer term).
- The total capacity of single-channel network = DWDM, but OTDM provide:
  - *potential improvements in network performance in terms of user access time, delay and throughput, depending on the user rates and statistics.*
- Less complex end node equipment (single-channel Vs. multi-channels)
- Can operate at both:
  - 1500 nm (like WDM) due to EDFA
  - 1300
- Offers both *broadcast* and *switched* based networks
OTDM - History

- 1985 S K Korothy et al - ‘High speed LiNbO3 as switch/modulator for OTDM’
- 1988 S Fujita - 10 Gbps systems
- 1993 A D Ellis - 40 Gbps
- 1998 M Nakazawa - 640 Gbps (60 km)
- 1999 P Tolire, et al - 100 Gbps Packet based
- 2000 K Yanenasu – 80 Gbps (168 km zero dispersion fibre)
Progress in Raw Speed

- 2000 - 40 Gb/s commercial product
- 1.28 Tb/s uses 200 fs pulses, using optical loop mirrors for demultiplexing (not possible electrically)

Source: W H Knox, 2000
Ultrafast Technology Impact on WDM and OTDM

- Source: DFB laser
- 10000 WDN is achieved using spectral slicing
Ultrafast Pulse Source

![Graph showing the relationship between 50 GHz Bandwidth, WDM channels, Pulse width (fs), and Commercial WDM 80 channels or more.](Image)
OTDM Broadcast
and
Switched Based Networks
A- Broadcast OTDM Networks

- **Bit interleaving:**
  - Each node will have a pair of OTDM Tx/Rx.
  - Just like broadcast WDM networks, it requires multi-channel media access protocol.
    - **Star:** Offers better link budget
    - **Bus:** Offers natural ordering of nodes, easier synchronisation and protocol design.

- **Packet interleaving**
  - No need for multi-channel media access control
  - Requires single-channel media access protocol
1- Bit Interleaved - *Multiplexer*

- **Data rate**: 100 Mb/s:
  - *Ethernet at 10 Mb/s,*
  - *Token Ring at 10 Mb/s,*
  - *FDDI at 100 Mb/s.*
Bit Interleaved - *De-multiplexer*

OTDM → **Splitter or star coupler** → Fibre delay $j\tau$ → Channel $j$
2- Packet Based

- Data rate 100 Gbps/channel
- Packet duration = 10 ns – 100 ps

Signal processing, switching and routing are carried out during guard band time.
Packet OTDM - *Multiplexer*

Mode-locked laser

Modulator

1\textsuperscript{st} stage

2\textsuperscript{nd} stage

\textit{i}\textsuperscript{th} stage

Mod. data

Compression

a)

b)

c)

d)

e)

OTDM

Pulse \(i\) location at the output is:

\((2^k - 1)(T - t) + (i - 1)\tau\)

\(T - \tau\)

\(2 \times (T - \tau)\)
Packet Compression

\[ I_{in}(t) = \sum_{i=0}^{N-1} I_i(t) = \sum_{i=0}^{N-1} \delta(t - iT)A_i \]

- For a single bit the composed output is:
  \[ O_i(t) = \frac{1}{2^{n+1}} \sum_{j=0}^{N-1} I_i[t - j(T - \tau)] \]

- The output signal for \( N \) bits packet is:
  \[ I_{out} = \sum_{i=0}^{N-1} O_i = \frac{1}{2^{n+1}} \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} I_i[t - (i + j)T + j\tau]A_j \]
Packet OTDM- *De-multiplexer*

Compressed packet

Control signals

Splitter

&

&

&

&
• Synchronisation of the control signal is essential to achieve accurate demultiplexing. This requires the extraction of a clock component from the received data using:
  • electro-optical
    - PLL
  • all optical at high speed > 40 Gbps
    - mode-locked fibre ring laser
Broadcast OTDM Networks - *Problems*

- Large splitting loss
- No routing or switching (signals are sent to all nodes)

**Solution:**

- **Switched based networks**
  - Tune-ability: select any time slot
  - Routing and switching
  - Much faster
B- Switched Based OTDM Networks

- Broadcast topology & media access protocol
  - Ethernet
  - Token rings
  - FDDI

- Store & forward topology
  - Mesh
  - ATM
  - IP

[Diagram showing network topology with nodes labeled 1, 2, 3, and 4, and labels for S/W & routing nodes and Source & sink nodes]
Switched Based OTDM Networks Node – Routing & switching

- Packet may specify:
  - Route chosen
  - Destination node (the choice of route is left to the routing nodes)

I/P buffers

Header recognition

DeMUX

Processing

To select o/p ports (use look-up table)

DeMUX

Processing

O/P buffers

Switch

Control Input
Switched Based OTDM Networks - *Header*

- **Header recognition:**
  - Optically (*more complex*)
  - Electronically

- **Techniques used:**
  - Transmit at a much slower rate than packet itself,
  - Allocate different wavelength
  - Transmit as a separate sub-carrier channel on the same wavelength
Switched Based OTDM Networks - Buffering

- Buffer size depends on:
  - Load
  - Packet loss
  - No. of input/outputs in a S/W

- Practical: 23 or more limited:
  - by the number of possible re-circulations within a loop
  - by the excessive hardware for larger buffer depth.

Solution:
- Multi-stage switched large optical buffer (>4000 for 8 input/output and 4 stages [D K Hunter et al, 1998]
Issues Associated with OTDM
OTDM - Issues

- High speed electronics:
  - Current ICs supporting 40 Gb/s will be available by 2001
  - 40 Gb/s receiver are already available

- Source: short pulse (tens of fs) and spectrally pure-
  - Gain switched semiconductor laser (broad source)
  - DFB laser (most suitable)
  - Mode locked fibre ring laser (pulse width < a few ps)
  - Semiconductor mode locked (higher pulse width and not as pure as MLFL)

- Multiplexing
  - Electro-optically *Passively

- 3 R regeneration:
  - using semiconductor optical amplifier *or nonlinear devices
OTDM - Issues – cont.

- Chromatics dispersion at 1550 nm is high, thus limiting the link span to 50 km at 200 Gb/s
  - use dispersion shifted fibre  
  - can’t use the existing fibre  
  - can’t compensate for a number of different wavelengths
  - use dispersion equalisation techniques
  - by concatenating different fibres of opposite dispersion signs
  - chirped fibre Bragg gratings
  - soliton pulse

- Polarisation mode dispersion - limits the bit rate
- Demultiplexing techniques and devices Π
- Buffering Π
OTDM Demultiplexing Techniques
OTDM - Demultiplexing Schemes

Electro-optic

All optical
Optical Demultiplexers – *All optical*

- **Two main technologies:**
  - Kerr effect in optical fibres
  - Fast nonlinearities observed in semiconductor amplifiers

**Types:**

- Optical loop mirror
- Interferometers with SA
- Four wave mixing
Types of Optical Loop Mirrors DEMUX

- **Loop mirrors:**
  - Nonlinear optical loop mirror (NOLM)- with/without external control pulse
    *intensity-dependent phase used as the nonlinearity*
  - Nonlinear amplifier loop mirror (NALM)
    *EDFA provides the nonlinearity*

- **Terahertz optical asymmetric demultiplexer (TOAD)**
  *SLA provides the nonlinearity*
A- Optical Loop Mirrors - Principle

Constructive interference
CW (\(\pi/2\)) + CCW(\(\pi/2\))

Intensity I

Destructive interference
CW (0) + CCW(\(\pi\))

Transmittance at port 2: \[ T_x(t) = 1 - \cos^2\left(\frac{\Delta\phi}{2}\right) \]

If \(\Delta\phi = \pi\), then \(T_x(t) = 1\) (i.e. 100% transmittance.)
1- NOLM Demultiplexer

- Control pulse will introduce nonlinearity

\[ T_x(t) = 1 - \cos^2(\Delta\phi / 2) \]

- If \( \Delta\phi = \pi \), then \( T_x(t) = 1 \) (i.e. 100% transmittance in port 2.)
2- Nonlinear Amplifier Loop Mirror

- The amplified CW pulse under-goes a larger phase shift compared to the CCW.
NOLM Model

• Maximised transmittance

\[ T_o T_w L\pi \alpha = 4\beta_2 \left[1 - \exp(-\alpha L)\right] \tanh \left(\frac{T_w L}{2T_o}\right) \]

• Switching profile

\[ W(t) = 1 - \cos^2 \left\{ \beta_2 \left[\frac{1}{T_o T_w}\right] \left[\frac{\sec h^2 \left(t/T_o\right) \ast \xi(t/T_o)\right]}{2} \right\} \]

\[ \xi(\tau) = \begin{cases} 
\exp \left(-\tau T_o \alpha / T_w \right) & \text{for } 0 \leq \tau \leq T_w L / T_o \\
0 & \text{for } \tau > T_w L / T_o \text{ or } \tau < 0
\end{cases} \]

where \( T_o \) is the pulse (soliton) width of the control pulse, 
\( T_w \) is the walk-off time per unit length 
\( \alpha \) is the fibre loss 
\( \alpha L \) is the interactive length of the fibre loop 
\( \beta_2 \) is the first order dispersion parameter
NOLMs DEMUX - Limitations

- Intensity dependent phase shift in Si fibre is a weak nonlinearity
- Long length of fibre (1 km) is required to achieve nonlinearity
- Nonlinearity is not easily controllable (i.e. to control an AND gate)
- Polarisations-maintaining is essential

Solution:
- Terahertz Optical Asymmetric Demultiplexer (TOAD)
B- Terahertz Optical Asymmetric Demultiplexer (TOAD)

- CW through SLA will face phase shift
- The SW window size = \(2n\Delta x/c\)
  (~ a few ps)
- Timing between control and data
  Pulses are critical
- SLA recovery time is large ~300 500 ps

\[
G_{TOAD} = \frac{1}{4} \left[ G_{cw} + G_{ccw} - 2\sqrt{G_{cw}G_{ccw}} \cos(\theta_{cw} - \theta_{ccw}) \right]
\]
All Optical Demultiplexing – *Reported works*

**NOLM based**
- 1994, S Kawanishi – 6.25 Gbps
- 1998, M Nakazawa - 640 Gbps
- 1999, K S Lee – Terabit

**TOAD based**
- 1993, A D Ellis – 40 Gbps
- 1999 B Mekelson - 160 Gbps
- 1996, A J Poustie - All optical circulating shift register
- 1998, A J Poustie - Optical regenerative memory
OTDM- Demultiplexers

Performance Issues
Residual Crosstalk - NOLM

- cw control pulses
- ccw signal pulses

- Loop mirror
- Coupler

- Depends on:
  - control pulse rate
  - control pulse width
  - walkoff time between control and signal pulses
Residual Crosstalk - TOAD

Depends on: - control pulse energy, - asymmetry, - SLA gain recovery time
Adjacent Channel Crosstalk

Depends on:
• shape of the switching window
• width of the signal pulse
Timing Jitter Noise
NOLM – *Noise and Crosstalk*

![Graph showing NOLM relative intensity noise and crosstalk](image_url)
**Crosstalk Comparison**

**NOLM**

- **CTX**
- **BTX**

**TOAD**

- **SLA L=0.3mm, Tasy=1ps**

**Switching energy (pj)**

**Crosstalk (dB)**

** bit rate: 100 Gb/s, and no. of channels: 10**
NOLM - BER

![Diagram showing bit error rate (BER) and optical power relationship]

- NOLM
- DEMUX
- BPF
- EDFA
- Error Detection
- Optical Receiver

Graph: Bit error rate (y-axis) vs. average received optical power (dBm) on x-axis. Key points:
- Baseline
- Walk-off time at 1ps, 9ps, and 18ps

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OTDM Applications
All Optical Router - *One Node*

- Crosstalk: Adjacent channel & Residual?
- Timing jitter?
- Bit error rate?
Clock Recovery Using TOAD

- Clock + data packet in
- Data packet out
- SOA
- PC
- Reflected clock pulse
- Fibre loop
- PBS
- Clock out
- 50:50
- SLA
- Clock out
- Data packet out
Series Router Configuration

Router 1

Router 2

Router 3

Router 3

Router 3

Router 3

P_0

P_{11}

P_{12}

P_{21}

P_{22}

P_{31}

P_{32}
Parallel Router Configuration
8x8 Banyan Network Architecture

Input lines

Output lines

000
001
010
011
100
101
110
111

110
High Speed OTDM Routing Networks
OTDM Routing Networks - Waveforms

Multiple copies of input frames generated within TSTs

Selected slot (sub cell) at the output of TSTs

Input to OTDM Dem.

Output port 2

OTDM Demux SW window

Sub cell

Sub cell
TOAD Based Packet Header Recognition - Parallel

- Can be extended to an arbitrary number of bits
- Only limited by the data and clock power available

SW window $\Delta t = \tau$
High Speed Optical Transport Layer

OTDM Add/Drop Demultiplexer

Input  ADM  Output

Drop

Add
OTDM Cross Connect

OTDM-λ1

1 2 3 4

ADM1

Add

Drop

ADM2

Add

Drop

OTDM-out

1 2 3 4

OTDM-λ2
LAN Application
Principle of 3R Regenerator
All Optical Networks / Existing Networks

IP

ATM

SDH

Open Optical Interface

SDH

ATM

IP

Other

All Optical Networks

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**OTDM and WDM - Comparison**

- 40 Gbps OTDM ≅ 16 Channels WDM 2.5 Gbps.
- For a 2 nm channel separation WDM would occupy the whole of EDFA bandwidth. **OTDM occupies only 1 nm of wavelength space**
- OTDM does require an active demultiplexer and channel alignment systems. WDM may also require accurate control of filter and source wavelength (DWDM).
- OTDM uses the available optical spectrum more efficiently.
- OTDM is less well advanced, and more costly than WDM, **BUT future research and progress may alter this.**
Challenges Ahead

- **Packet Routing**
  - Algorithms
  - Bit error rate and Packet error rate Analysis
  - Dispersion control (use soliton)
  - Crosstalk analysis
  - Buffering
  - Intelligent based routing

- **OTDM Based Cross Connects**
  - Size
  - BER and Crosstalk analysis
Remarks

- OTDM is a powerful technique for delivery of high capacity backbone, as an alternative (but not a substitute) to WDM
- Nonlinear devices can be used as an all optical demultiplexer
- OTDM data rate can be increased and its performance improved by employing soliton pulse
- Commercial realisation depends on future advancements in integration techniques, and devices etc.
- The development of the capacity is not the ONLY GOAL. The flexible use of this potential and advantages of optical routing are the KEY FACTORS in the development of optical network.
- Technologies should develop, integrate with and enhance those already existing.
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Packet Switched Optical Network - Internal node structure

- Single wavelength packet
- Bit rate of 100 Gbps