The Evolution of Optical Communications

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The North American networks after the de-investiture of AT&T
• Voice will stay separate from data.
• Each service provider will address new services in the context of its operations.
• The QoS for voice and data will stay different.
• Voice and voice related services will continue to grow.
• Voice services will continue to be profitable.
What actually happened and is happening

- Data have overtaken voice in traffic volume.
- Voice brings 80% of the income but uses 10% of installed information capacity.
- Data bring 20% of income but use 90% of the installed information capacity.

- Voice over IP enhanced the income of data services.
- The cable TV companies provide voice services.

The RBOCs and their equivalents have their lunch stolen under their noses!!
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Forecasts

Carrier VoIP minutes (in billions)

Sources: In-Stat/MDR; Morgan Keegan & Co

Telephone company

Cable

Forecasts

Total broadband voice lines (in millions)

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• Developed independently.
• Different market segments and different customer expectations.
• Capital and operational expenses different.
• Different time horizons for borrowing and paying back.
• Different reliability requirements.
Eliminate the boundaries

Transformation

Deliver ubiquitous and seamless services

Services

Wireline

Wireless

Voice

Data

Public

Private

Broadband Connectivity
**End-User**

- Office computer
- Office phone
- PDA
- Mobile phone
- Home computer
- Home phone

**Opportunities**
- Simplified user experience
- Service integration
- Quality of service
- Bandwidth

**Enterprise**

- Headquarter
- Branch
- Branch

**Opportunities**
- Application management
- IT centralization
- Collaboration
- Security

**Service Provider**

- Opportunities
  - Network simplification
  - Service integration
  - Cost containment
  - Service revenue retention
- Dramatically lower in cost
- Always on
- Anytime, anywhere and in any form
- Voice and multimedia
- Self service, intuitive
- Simpler for the end user
- Secure, trusted and reliable
- “Platform” for “services” creation

Key characteristics of the future network

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Transforming the network: The vision

Today
- Multiple networks
- Simple devices
- Disparate services

Transition
- Converged packet network
- Multimedia devices
- Linked services

Transformed
- Dynamic packet / broad band optical network
- Secure multimedia services
- Ubiquitous broadband
- Integrated functionality
The realisation of this vision will require the operation of three classes of networks which already exist, as

*Access network*
*Metropolitan area network*
*Long haul network*

*And new networking approaches*

**BUT** the services must be delivered to the end user with

**Cost Effectiveness**

in terms of Capex and Opex.
The seven layers of the OSI will be reduced to may be three or four delivering:

- Single services platform
- Cost reduction (CapEx)
- Maintenance simplicity (Opex)
- Space and power savings
- Some management may be moved to the physical layer if cost effective

The typical example of layer merging is IP over WDM Layers 1 and 3
The fibre access network has been researched during the last twenty years worldwide in terms of

Technology
Architecture
Services
Networking

But after all this worldwide research the cost effective service delivery is still based on copper. *Coaxial cable or twisted pair*

*Why?*
Technology for access

Cost effective optical technologies are available.

Architectures

Cost effective architectures have been identified and multi-service platforms are currently been introduced.

Services

No “killer” application has been identified yet.

The key cost issue is that of installation. It takes nearly £1000 to dig up the street and installed fibre to the home!
What can be done?
There is no doubt that fibre provides the maximum bandwidth and if installed then any future service upgrades will not be limited by bandwidth.

Two approaches
Government intervention (fibre to the home - Japan and South Korea)
Market forces (the rest of the world – copper therefore prevails)

Other technologies under study
Radio, free space optical
The project IST FP6 MUSE
Scope
  Low cost, Full service access and edge network for ubiquitous delivery of broadband services to all European users.

Objectives
  Study Access technologies and techniques that
    Offer low cost
    Support migration
    Support many Europeans: multiple first mile solutions
    xDSL and FWA

Provided by Prof. S. Walker - UoEssex
Approach

FttH migration support
FttP deployment scenarios
Installation aspects
Service support and evolution
Techno-economic analysis
Access demonstrators

E2E Access- Gateway demonstrator
FttX technology prototypes

Provided by Prof. S. Walker - UoEssex
The generic MUSE architecture

Provided by Prof. S. Walker - UoEssex
Features

System length 50 – 600 km
Capacity multi-wavelength 2.5 – 10 Gbit/s
Amplifiers EDFA (possible QDA)
Configuration Mesh or ring
Special features ADM at every amplifier site
Very cost conscious
Device cost
Directly Laser Processing
Electronics
Applications to MANs

Storage scope emulates A/D converter
Computer emulates ASIC

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Results for directly modulated laser at 10 Gbit/s ASK – DSP

DSP technique can retain $10^{-3}$ BER in spite of eye closure
Error floor at $\sim 10^{-4}$ at 320 km
Interferometer demodulator at transmitter converts PSK to low chirp ASK

Interferometer could be shared between channels at transmitter
Interferometer could be placed at receiver with balanced detector

ASK is transmitted into fibre
Results for directly modulation 10Gbit/s P-ASK – DSP

DSP technique improves back-to-back performance
Over 300 km for 5 dB OSNR penalty
Large total dispersion tolerance could be accessed using a optical dispersion element (grating)
Two extreme options

*All the intelligence in the periphery*

- Very good control (electronic)
- Easy to upgrade
- Bottleneck of electronics

*All the intelligence in the core*

- All optical control questionable
- Electronic control expensive
- No bottleneck of electronics

*The jury is out but the first option is the favourite at the moment!*
Previous rapid capacity growth could only be met by exploiting optical technology:
- For reach: Raman and hybrid amplifiers
- For capacity: high wavelength count DWDM system

By 2003, Si electronic capabilities caught up
- Signal Processing capabilities could be exploited for transmission product design
- Alternate technologies/solutions can be introduced
To capitalise on the availability and low cost of fast electronics

- **Remove all the optical processing to the terminals.**
  - Chromatic dispersion compensation
  - Polarisation mode dispersion
- **Simplify the optical amplifier architecture.**
  - Single stage optical amplifiers
  - Lower noise figure
  - Lower gain
- **Use advanced modulation formats**
  - Higher spectral efficiency
  - Advanced signal processing techniques

Use optics and electronics to the best of their abilities!!
The Evolution of Optical Communications

Simplification of the optical system

Higher Spectral Efficiency
Remove C+L or costly wide band amplifiers
Minimises the cost of installation by using DCM of standard dispersion and add flexibility through ESP
Remove Raman, Increase Performance

Electrical Signal Processing
Advanced FEC

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The Evolution of Optical Communications - 28
• **Dispersion compensation**
  – *Adaptive compensation – chromatic and PMD*
  – *Variable length of operator – compensates for variable length of fibre*
  – *Automatic set up – the algorithm identifies the initial conditions*
  – *Blind compensation possible (no training sequences)*

• **Signal processing**
  – *Maximum likelihood sequence estimation (MLSE)*
  – *Soft threshold decisions*
  – *Forward error correction (FEC) (1)*

(1) The only signal processing used at the moment
Issues limiting the deployment of 40 Gbit/s systems

**Dispersion**

*Limited chromatic dispersion tolerance (~100 ps/nm)*

*Limited PMD tolerance (~10 ps)*

**Technology**

*Immature high speed electronics (high cost)*

*Immature optical adaptive compensation technologies (high cost)*

**DQPSK offers a different approach from ETDM**

*Implementation of 40 Gbit/s using lower symbol rate such as 10 Gbit/s*

*Significant advantages in system tolerance*

*Higher spectral efficiency*
Integrated 20 Gbit/s (2x10 Gbit/s) DQPSK data modulator (GaAs or LiNbO₃);
Integrated π/2 phase control between I-/Q-channels;
Carrier-suppressed RZ for more advanced modulation;
Polarization multiplexing to deliver a capacity of 40 Gbit/s per wavelength;
Spectral efficiencies significantly higher than those of ETDM

1.6 bit/s/Hz back-to-back spectrum shown with a typical signal eye before decoding
Polarisation demultiplexing from 40 Gbit/s to 20 Gbit/s
DQPSK decoding based on a 1-bit-delay M - Z interferometer with a differential phase shift of $\pm \frac{\pi}{4}$
Active stabilisation of DQPSK decoder phase required
Balanced detection of I/Q channels
Polarisation extinction of more than 30 dB at back-to-back

![Graph showing power (dBm) vs. wavelength (nm) for filtered 40G TE and filtered 40G TM wavelengths.](Image)
8-fold extension (for 1 dB penalty in Q) of typical 40 Gbit/s dispersion tolerance in the absence of any adjustable dispersion compensator.

- CSRZ-DQPSK
- CSRZ-IMDD

Chromatic dispersion (ps/nm)

Q penalty (dB)
Doubling of 40 Gbit/s PMD tolerance in the absence of any adjustable PMD compensator

- **CSRZ-DQPSK**
- **CSRZ-IMDD**
Achievable mid-channel transmission performance

FEC threshold
Intensity modulation / direct detection format

Simple and efficient format
Propagation well understood
Design and implementation well understood
Dispersion compensation – optical (DCF) well understood

Electronic compensation – complex installation

Electronic compensation – limited value because of the non linear process of optical detection
What can be done

Basic observation
Dispersion is a linear operation on the optical electrical field (E - field). As a consequence, its direct effects can be removed by linear filtering proportional to the complex E-field.

Approach
[a] coherent detection
[b] electronic pre compensation in amplitude and phase

At this stage electronic pre-compensation is the cost effective approach
Electronic dispersion compensation

Real (red) and imaginary (blue) parts of the impulse response which pre-compensates for 51,000 ps/nm of fibre dispersion. The x-axis is the number of past and future T/2 taps.

Optical E-Field modulator with separate in phase (I) and quadrature (Q) drives.

Electronic pre-compensation (OFC ‘05, OThJ3)
Electronic pre-compensation processor

Required OSNR (dB) vs. reach (km NDSF) pre-comp Tx with...
First definition

process without access to the signal baseband
- wavelength conversion
- optical regeneration
- optical switching

If these functions can be performed electronically the lower cost of electronic will ensure that they are done electronically!

Second definition

process optically the signal baseband
- essentially bit by bit process of information
- imitating electronics but at much higher speeds hopefully!

Approach still in its infancy
The challenge

The generic architecture of an all optical wavelength converter highlighting issues of complexity for use in the network.
Fibre loss characteristics

Loss ≤ 0.4 dB over 415 nm (1260 – 1675 nm)
## Options and technologies

<table>
<thead>
<tr>
<th>Band</th>
<th>Meaning</th>
<th>Wavelength (nm)</th>
<th>Amplifier Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Original</td>
<td>1260 - 1360</td>
<td>Praseodymium ?</td>
</tr>
<tr>
<td>E</td>
<td>Extended</td>
<td>1360 – 1460</td>
<td>Raman ?</td>
</tr>
<tr>
<td>S</td>
<td>Short</td>
<td>1540 – 1530</td>
<td>Raman or Thulium ?</td>
</tr>
<tr>
<td>C</td>
<td>Conventional</td>
<td>1530 - 1565</td>
<td>Erbium</td>
</tr>
<tr>
<td>L</td>
<td>Long</td>
<td>1565 - 1625</td>
<td>Erbium</td>
</tr>
<tr>
<td>U</td>
<td>Ultra - long</td>
<td>1625 - 1675</td>
<td></td>
</tr>
</tbody>
</table>
Semiconductor Optical Amplifiers, (SOA)
Quantum Dot Optical Amplifiers (OFC '04; PD 12)

Summary of QD SOA device performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>120 nm</td>
<td>nm</td>
<td>170 nm for gain of 20 dB 220 nm for gain of 10 dB</td>
</tr>
<tr>
<td></td>
<td><strong>(1410 – 1530)</strong></td>
<td><strong>nm</strong></td>
<td></td>
</tr>
<tr>
<td>Noise figure</td>
<td>5 - 7</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>&gt; 20</td>
<td>dB</td>
<td>For 120 nm bandwidth</td>
</tr>
<tr>
<td>Saturation power</td>
<td>25</td>
<td>dBm</td>
<td>Systems operation usually 3-4 dBm below saturation</td>
</tr>
</tbody>
</table>

If this result is repeatable then through development this class of device will definitely challenge the EFDAs; however cross talk and reliability are still unknown.
Semiconductor Optical Amplifiers, (SOA)

CWDM 16 channels!

Amplifier gain
Hatched area corresponds to gain > 20 dB

Quantum Dot Optical Amplifiers (OFC '04; PD 12)

BER and eye diagrams for 10 Gbit/s
Summary

EDFAs will dominate the applications and especially C-band operation in other bands will be hindered by cost and complexity.

SOAs seem to have a window of opportunity in DWDM and CWDM.

QD amplifiers →
- Broadband operation
- High power
- Absence of patterning
- Cross talk (?)
- Reliability (?)
• **Networks**
  Convergence of “everything” into packets – Security may be an issue
  Convergence of the OSI into fewer layers.
  Network intelligence concentrates in the edge.
  Network evolution towards the use of optical signal processing.
  Optical packet switching / burst mode switching

• **Transport - Electrical Time Domain Multiplexing (ETDM)**
  ETDM will return with the associated requirements for optical chromatic compensation, PMD compensation etc but it will take longer than it was thought.
  Optical time division multiplexing, (OTDM), will prevail above 80 -100 Gbi/s

• **Electronics**
  Electronic signal processing will establish itself in optical fibre communications.

• **Optical signal processing**
  Optical switching will be consolidated and in wide use.
  Wavelength conversion will have an opportunity with rates at 160 Gbit/s and beyond.
  Optical regeneration will have an opportunity with rates at 160 Gbit/s and beyond.
  Optical signal processing for optical packet switching
**Electronics**
- Technology
  - 90 nm CMOS and shorter channel
  - InP with high density of devices
- Processing
  - Signal processing for nonlinear channels
  - Adaptive signal processing

**Optical systems**
- Beyond 40 Gbit/s
- Propagation issues including solitons
- Optical time domain demultiplexing (OTDM)
- Adaptive subsystems
- Use of “2R” and “3R” regenerators
- High spectral efficiency formats
  - Optical packet switching
- Architectures
  - Protocols
    - Access architecture
    - Service introduction
    - Wireless / optical access
    - System simulation

**Optical Devices**
- Mode locked lasers for pulse generation
  - 40 Gbit/s and beyond
- Optical time domain multiplexing & demultiplexing
  - 160 Gbit/s and beyond
- Low cost devices for access
  - But is this the key issue?
- SOA for Metropolitan Area Network
  - High power, low cross talk, broad band
- Glass Optical amplifiers
  - 1300 nm to 1700 nm
- Fast optical switches
  - Nanoseconds and faster for optical packet switching
- Optical regeneration
  - Integrated single wavelength regeneration

**Optical signal processing**
- Pattern recognition for address identification
- Spatial control of light - static and dynamic –
- Photonic crystals
- High D - value dispersion compensation –
- Photonic crystals
Quantum Communications

- Optical communications with chaotic light
- Quantum Cryptography

Technologies

- Nanotube electronics
- Spintronics
- Quantum dots
- Photonic crystals for devices and transport fibre
- Photonic crystals combined with optical sources

Optical technologies and signal processing are the foundations of the broadband optical network of the future

Thank you for your time