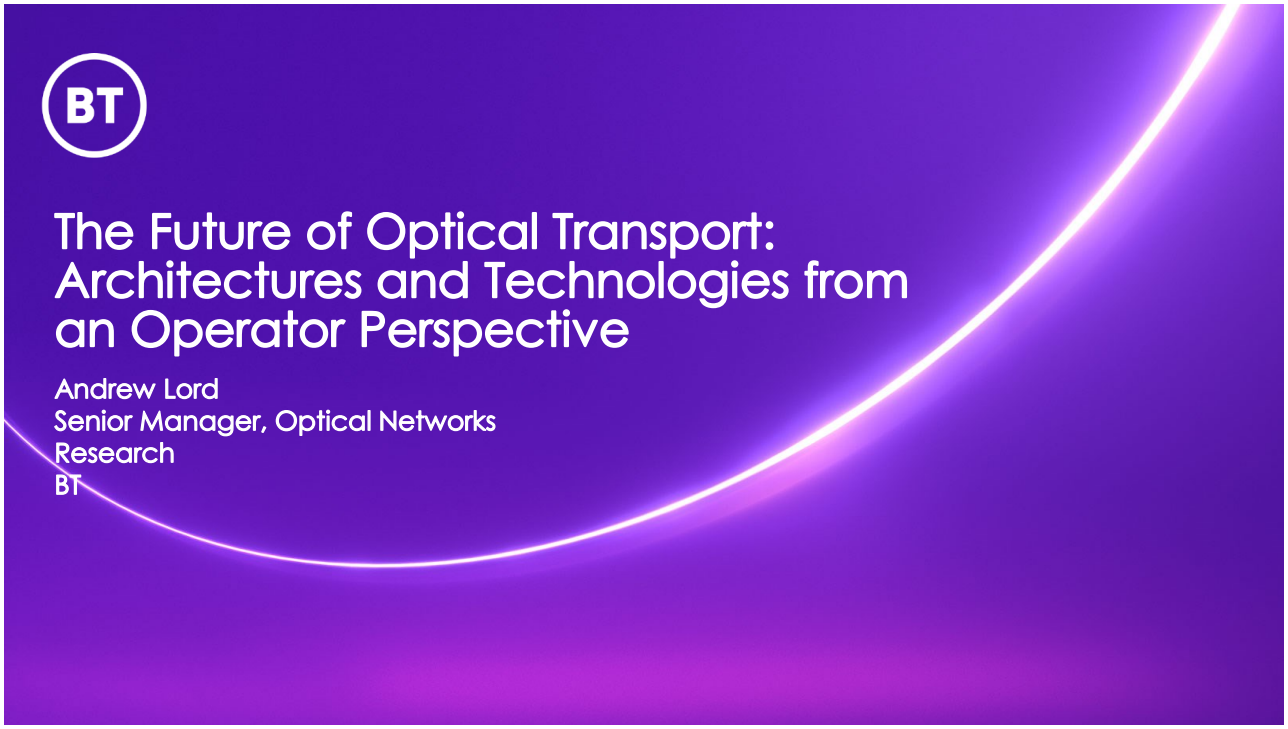

1

The Future of Optical Transport: Architectures and Technologies from an Operator Perspective

Andrew Lord
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Andrew.lord@bt.com

Abstract: This tutorial paper reviews recent developments in optical transport architectures from an operator's perspective, focusing on how coherent technologies will push towards the network edge

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Talk outline

Introduction

Optical transport summary of where we've got to

Description of main forward-looking requirements / pressures

Focus on core transport networks

Focus on metro networks

Other issues becoming increasingly important
Optical network security
Power consumption

Conclusions and outlook

3

Talk outline

Introduction

Fibre is the 21st century copper. There is nothing else. The journey has to last > 100 years

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Fibre – a 21st century global mega project

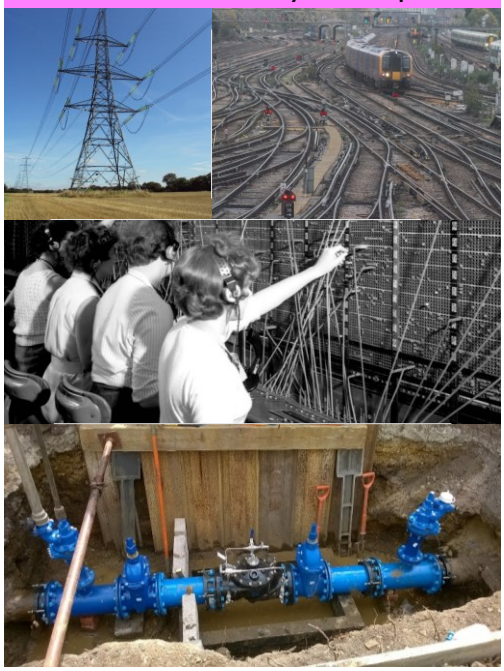
19th / 20th Century saw massive world-wide infrastructure projects
- Railways, electricity grids, water supplies, telephone networks based on copper

21st Century is also seeing massive world-wide build
- High bandwidth wireless access
- Optical Fibre to billions of homes and wireless networks

The fibre already installed is a small fraction of what is to come
- World-wide project will take decades
- Cost $100s bns
- Will have to endure for ~100 years or more

Optical technology underpins the future
- Essential for all future 5G++ networks
- Essential for all consumer internet
- Essential for all future smart cities, IoT

Fibre to homes / 5G cells is a century-scale investment with century-scale impact



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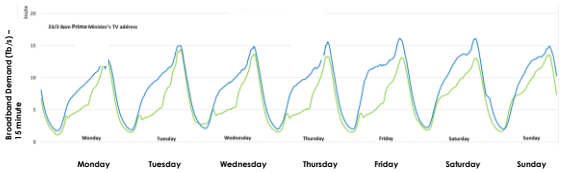
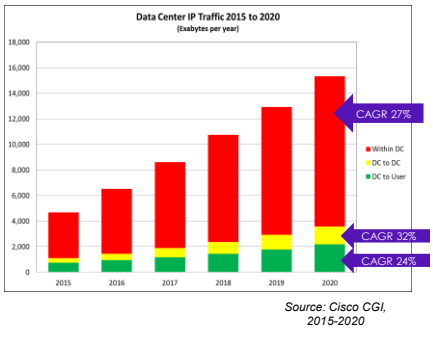
Network traffic growth



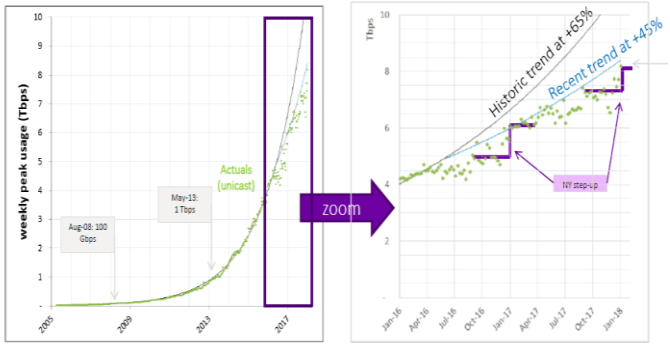
Daily traffic during COVID

Global averages



Source: Cisco CGI, 2015-2020

A BT central core router



25Tb/s now = 500Tb/s in 10 years – but needs to cost the same!

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Talk outline

Introduction

Optical transport summary of where we've got to

DWDM + increasing transceiver rates has fuelled 20 years growth
Network simplification – box reduction maintained network cost effectiveness

Description of main forward-looking requirements / pressures

Focus on core transport networks

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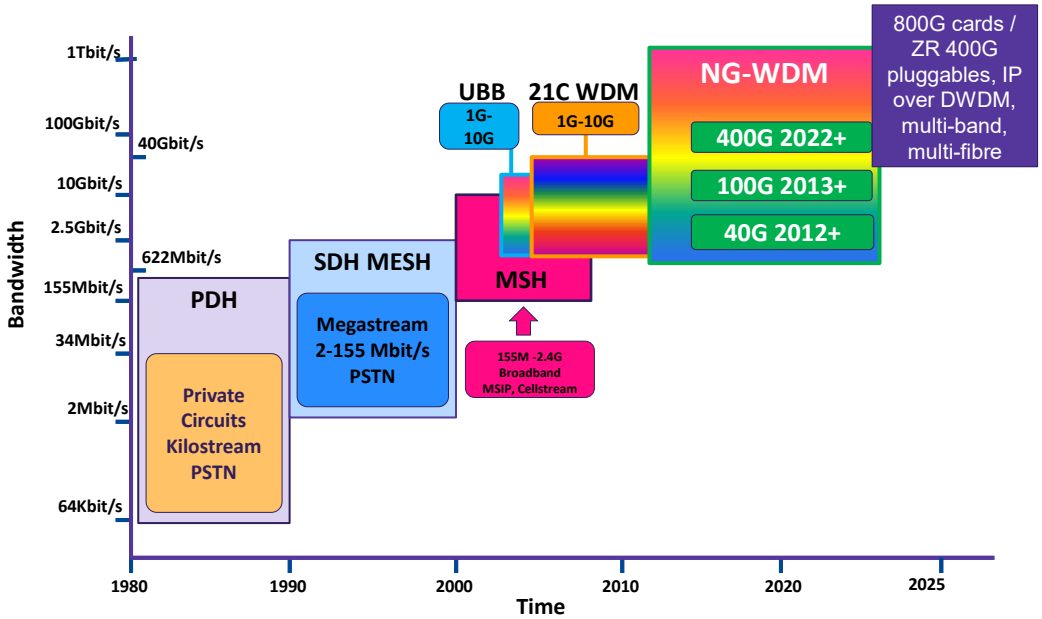
BT example of multiple network solutions



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Evolution of optical networks – elimination of boxes

Past 20 years – complex, multi-layer networks have been stripped back to the Lowest Common Denominator

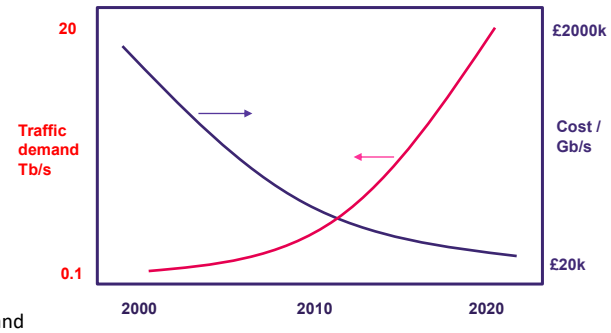
- Cost per bit has fallen by a factor of 10 or more
- Enabled by new technologies and network simplification

Networks perform:

- Access collection
- Aggregation and switching
- Transport

Most of the architectural simplifications have now happened

- Still incremental opportunities
- IP over DWDM reduces grey optics and assists with power and space
- Photonic integration fuelling current high speed optical solutions
- Photonics in routers next?



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Talk outline

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Optical transport summary of where we've got to

Description of main forward-looking requirements / pressures

Maintaining 20-30% traffic growth / year given spectral efficiency limit, Moore's Law limit and energy constraints.

Focus on core transport networks

Focus on metro networks

Other issues becoming increasingly important
Optical network security
Power consumption

Conclusions and outlook

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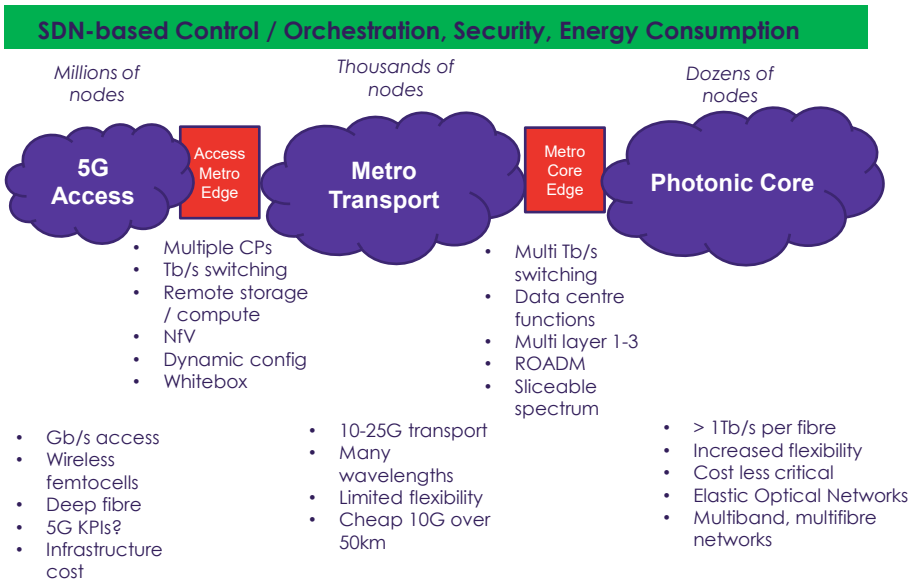
Lowest Common Denominator Network?



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Shannon and Moore – not long for this world….

- Shannon's law defines total capacity in a channel.
- Optical transmission is nearing this capacity limit
- Higher data rates = shorter distances
- We can no longer simply increase the data rate

- Moore's law predicts silicon speed doubling every 2 years
- But this is slowing down
- And associated power dissipation has become a huge problem in Data Centres and networks

How do we continue to provide 30% annual traffic growth when both our fibre and electrical switching are hitting limits?

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Balance between multiband and multifibre. Multiband will struggle to go beyond C + L given availability of huge fibre count cables.

Focus on metro networks

Other issues becoming increasingly important
Optical network security
Power consumption
Conclusions and outlook

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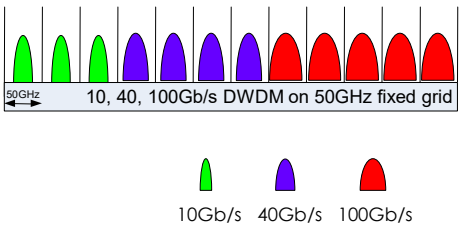
Core Evolution – early 2000s - ~ 2020

- Existing optical flexibility:
- Fixed (arbitrary) ITU 50GHz wavelength grid
- ~ 90 fixed slots for optical signals (10, 40, 100Gb/s)
- ROADMs
- Wavelength slots can be switched to any output independently



BUT THE TRADITIONAL SLOTS ARE GETTING FULL….

14

400G ZR – the next step

What is it?

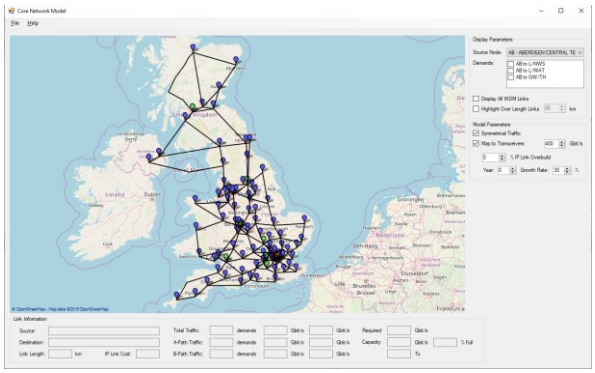
- 100Gbit/s migration to 400Gbit/s with a refresh of both the IP and optical layers
- Data centre driven the development of 400G-ZR pluggable
- QSFP-DD interface of 400Gbit/s switches and routers, can reach up to 120km
- By making use of these new modules, this means that for the first time network operators could have IP-optical integration

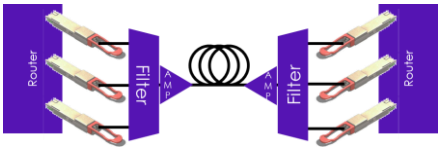
Hop to hop between routers costs in??

- In places – especially highly dense parts of the network
- Optimum solution is a hybrid of ZR, ZR+ and conventional transponders
- Volume pricing offsets the hop-hop architecture

Router + ZR integration needs to be validated

- Next stage is integration validation





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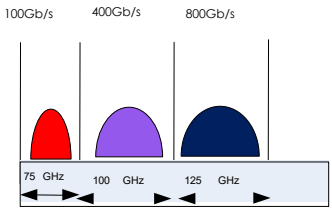
Elastic optical networks? 2020 - 2030

- Two types of elasticity / flexibility:
  - Transceiver-based. Single transceiver capable of different modulation formats / overall rate
  - Spectrum-based or flexgrid. ROADMs capable of dividing up the spectrum into arbitrary chunks of spectrum
- Transceiver flexibility
  - Single transceiver can adjust baud rate and modulation format
  - Each combination will have a different performance / OSNR / distance capability
  - Flexing transceivers will allow the network to run close to the maximum capacity
  - Downgrading also an option in case of increasing link loss etc
  - IP layer (if used) will need to understand this optical layer capability
- Flexgrid
  - ROADMs can be adjusted to different spectral slots to accommodate different baud rates
  - Different vendors have different baud rate capability
  - Fixed spectrum can be wasteful (estimated around 20-30% in many models = 1 year's network gowth!)
  - But spectrum management will be a major head-ache
- Larger fixed grid
  - 50GHz could become 75GHz, 100GHz or even 125GHz to contain bigger baud rates
  - Fixed grids easier to manage than flexgrids.
- Multiple optimisations have led to much discussion around AI / ML.
  - Would an operator entrust critical network deployment to AI?



"Flexible Technologies to Increase Optical Network Capacity", Lord, Mitra, Tornatore, Savory – to be published in Proc.IEEE soon

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Why Beyond C Band Optical Networks?

- C band is becoming congested
- Shannon's Law reaching a limit on spectral efficiency
- Distances for high QAM transmission are reducing – see ZR optics
- Alternatives are
  - Increase number of fibres from 1 to N
  - Increase transmission bands from 1 to M and ultimately increase fibres from 1 to N / M
  - 30% traffic growth = x10 within 9 years (10 fibre pairs for C band only, 5 FP for C+L band, 2-3 FP for multi-band)
  - Multiband can buy operators time
  - But implies expensive research investment by vendors
- Question – when is Cost of Development of Multiband > Cost of new fibre cables ?

Name	O	E	S	C	L
Wavelength range (nm)	1260-1360	1360-1460	1460-1530	1530-1565	1565-1625
C-band system				35 nm	
C+L-band system				95 nm	
Average fiber loss [dB/km]	0.36	0.28	0.22	0.18	
Multi-band	365 nm				

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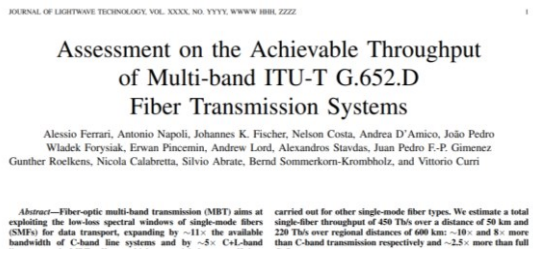
How much capacity is available?

Network size	C	C + L	O - L
50km	45 Tb/s	180 Tb/s	450 Tb/s
600km	28 Tb/s	90 Tb/s	220 Tb/s

- Results are network dependent
- Assume standard SMF fibre
- Various assumptions about amplifiers etc
- Should be seen as ultimate target / limit
- Some approaches consider using O band for Raman pumps
- Nevertheless – it is an important paper with highly useful general guidelines for deciding the need for multi-band



JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. XXXX, NO. YYYY, WWWW HHH, ZZZZ

Assessment on the Achievable Throughput of Multi-band ITU-T G.652.D Fiber Transmission Systems

Alessio Ferrari, Antonio Napoli, Johannes K. Fischer, Nelson Costa, Andrea D'Amico, João Pedro Wladek Forysiak, Erwan Pincemin, Andrew Lord, Alexandros Stavdas, Juan Pedro F.-P. Gimenez Gunther Roelkens, Nicola Calabretta, Silvio Abrate, Bernd Sommerkorn-Krombholz, and Vittorio Curri

Abstract—Fiber-optic multi-band transmission (MBT) aims at exploiting the low-loss spectral windows of single-mode fibers (SMFs) for data transport, expanding by ~11× the available bandwidth of C-band line systems and by ~5× C+L-band carried out for other single-mode fiber types. We estimate a total single-fiber throughput of 450 Tb/s over a distance of 50 km and 220 Tb/s over regional distances of 600 km: ~10× and 8× more than C-band transmission respectively and ~2.5× more than full

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Fibre resource availability

- Fibre costs vary considerably
- Some operators have to lease fibre
  - Lease costs highly variable e.g urban vs rural
- Some duct routes are highly congested, making it hard to install new cables
- But there are enormous fibre count cables available – up to 6912 fibres
  - Assuming a C band capacity of 20Tb/s (= 100 wavelengths x 200Gb/s)
  - 30% traffic growth will fill this 6912 fibre cable within 30 years.
- Procurement of large count cables is (probably? PAYG?) an up-front cost
  - Multiband can be added to existing fibres as required (with some precautions)
- Example – after 10 years
  - Assuming day 1 capacity of 20Tb/s (conservative estimate)
  - After 10 years this = 212Tb/s
  - Which equates to ~ 10 C band fibres
  - Or ~ 5 C + L band fibres
  - Or perhaps 2 – 3 multiband fibres

Given that only 10FP can deliver enough capacity for next 10 years…. Do we need to worry about multiband?

Exponential growth never continues for ever…
Fundamental physics laws intercept (power, space etc)
Human capacity to absorb information (eye, brain)
But M2M could = 10x M2H
Then there's the Metaverse…

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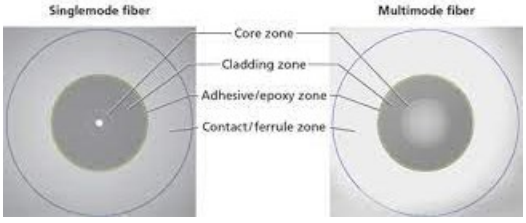
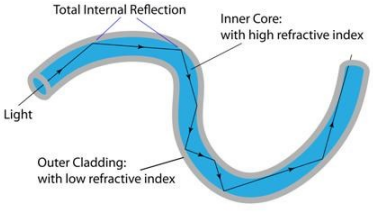
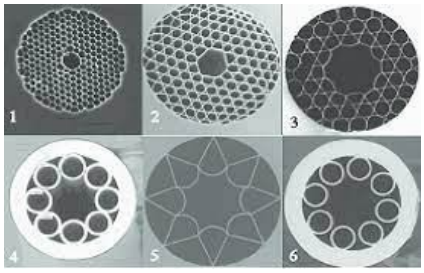
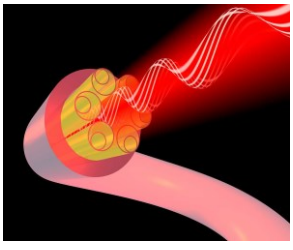
What about a new type of fibre?





Standard Glass fibre that we use in our network





New Hollow Core fibre

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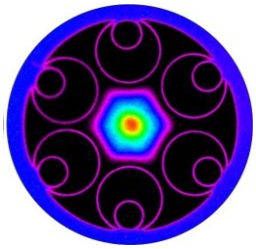
Why Have Optical Guidance in Air?



Cross Section of NANF
(Nested Anti-Resonant Nodeless Fibre)
showing single mode guidance in the centre

Ultra-low nonlinearity
HCF has no detectable spectral change due to Self phase modulation. **More power into the fibre and aids Quantum technology**

Low Latency
HCF has 1.54µs/km lower latency than single mode, that's **30% faster than our current fibres**.

New Transmission Bands
HCF opens up the possibility of using spectrum that we could not before. **Lower cost transmission.**

Low Thermal Sensitivity
HCF has a sensitivity of 2ps/km/K, 20 times smaller than SMF. So temperature changes do not affect latency. **Ideal for timing.**

Low Chromatic Dispersion across all wavelengths
HCF dispersion is 2ps.nm.km. In single mode fibre dispersion increases in the C-band. **This means lower cost optics.**

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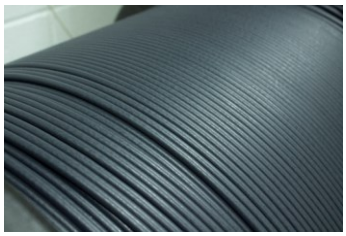
BT Tested Use Cases

HCF has already been deployed in New York and London for high frequency trading taking advantage of its inherent low latency.

BT had a field deployable cable on loan for 3 months and tested three different use cases.



Mobile: Ability of HCF to increase 5G mobile network fronthaul distance due to lower latency.

Metro/Core Networks: Ability of HCF to remove amplifier nodes and increase reach.

Quantum: Ability of HCF to place a quantum secure channel right next to a data channel.

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Focus on metro networks

Cost is king in the metro. Cost is driven by volume. Volume could come from 5G / DCI. Coherent vs non-coherent unresolved. How far can coherent push to the edge?

Other issues becoming increasingly important
Optical network security
Power consumption

Conclusions and outlook

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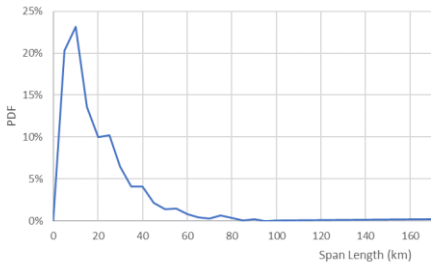
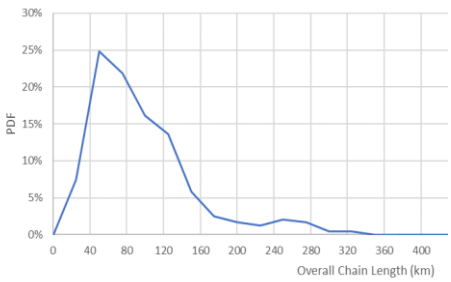
Metro topology statistics

- **What does the BT metro look like?**
  - ~1000 local exchange nodes connecting to ~100 metro-core nodes
    Chains of between 5 and 10 nodes (horse-shoe) to two metro-core nodes
- **What is happening to traffic?**
  - Continuing the 30% / year growth curve
- **What will 5G mean for the metro?**
  - One network - metro carries everything – consumer broadband, enterprise traffic, 5G
    Macro cells densifying to small cells… 10Gb/s – 25Gb/s





Distances modest, line-rates approaching the IMDD-coherent watershed, architecture hubbed, highly cost-sensitive part of the network

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Some optical transport options

	Non-coherent	Coherent
Point to multi point	▪ PON – GPON far too small for metro ▪ PON – 25 / 50GPON still small but useful for small cells?	▪ PON – coherent / WDM PON ▪ **XR Optics using Digital Subcarrier**
Point to point	▪ 10Gb/s DWDM (legacy) ▪ 25Gb/s DWDM (NRZ) ▪ PAM4 (25 / 50G?) ▪ Kramers Kronig ▪ G.Metro ▪ Pt-pt using PON technology	▪ 100Gb/s DWDM ▪ ZR (400G) – too big? ▪ ZR (100G) – industry traction? ▪ < 100G coherent pt-pt too expensive?

… plus optical switching options ranging from filterless to full ROADM and including 1x2 ROADMs, potentially with photonic integration

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Point – Multipoint coherent: XR Optics

Head-end coherent XR 400Gb/s Transceiver

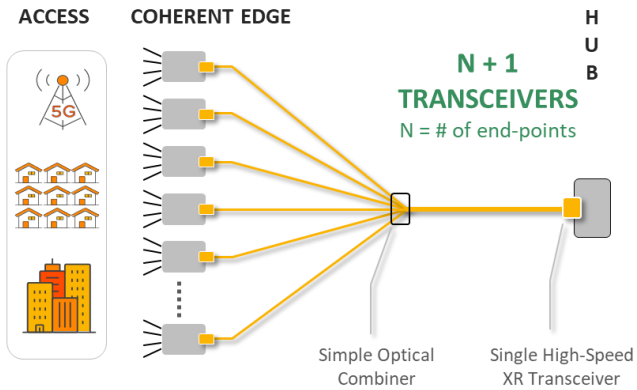
Passive splitter / combiner as with PON

Lower rate edge transceivers (e.g. 25G, 100G)
16 simultaneous coherent optical line systems
DSP-locked spectrum: ***Digital Subcarrier***

Huge reduction in transceiver count for hubbed architectures with asymmetric traffic

Additional benefit of automatic multiplexing

Also provides agile traffic provisioning



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Joint modelling work

- Presented at ECOC 2020 and ECOC 2021
- Technology comparisons over typical BT topologies
- Assumptions made on component costs, traffic levels and growth etc – see the papers for details
- Massive savings for XR due to (i) fewer transceivers, (ii) reduced multiplexing

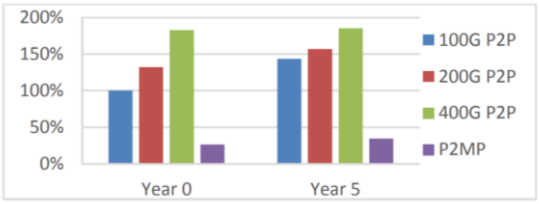
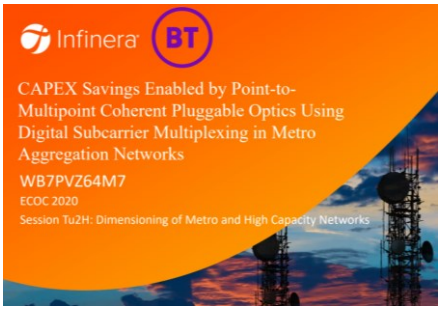
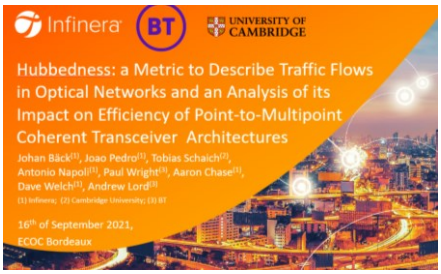


Fig. 2 Normalized cumulative CAPEX for different P2P transponder data rates compared to P2MP transceivers.





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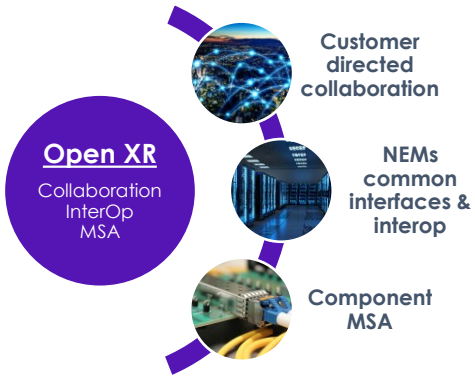
Open XR Forum

- Purpose
  Accelerate time-to market and broad market adoption of point-to-multipoint (P2MP), coherent fiber optic networks
  - Establish interoperability between low speed and high-speed coherent modules, enable SW configurable bandwidth, define compatibility requirements with 3rd party hosts
  - Establish a supply chain ecosystem to provide assurance of supply and serve a diversity of applications and geographic markets
- Organization
  - Core group of carriers establish governing rules & directives
  - MSA Members to establish multi-source Specification
  - Participant Members to advise and provide additional application requirements
- XR MSA Group
  - Define common interfaces, promoting interoperability and multi-sourcing at various levels of integration
  - Enabling technology licensing programs and/or product availability
  - Selected technology partners will be invited to join the consortia to ensure multi source capability & interop



https://www.openxrforum.org/

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Other issues becoming increasingly important
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Conclusions and outlook

Security concerns pushing for network layer security – is PQC enough or will QKD become more than a niche solution? Power consumption (heat and fuel bills) impacting operators much more now than 10 years ago – could this drive new architectures?

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BT's interest in Quantum Communications

- BT has spent several years integrating QKD with mainstream transmission for full-service quantum encryption. We have a lot of experience in doing this now
- We have spent a lot of time working with potential customers – educating / understanding requirements
  - Customer curiosity around quantum has exploded over the past 12 months coupled to QC progress
- We have built a range of demonstrators and trials:
  - Integrated QKD + classical WDM with Toshiba and Adva
  - Quantum Comms Hub QKD system between Adastral Park and Cambridge – IDQ + Adva
  - Customer QKD trial with National Composite Centre in Bristol – with Toshiba and Adva – over Openreach commercial fibre product
  - A range of lab demos
- We have more recently been building internal business cases / propositions for a QKD service
  - Still a Work in Progress
  - What will be the impact of NIST-approved mathematical solutions in ~ 2 years?
- Contract signed with ArQit to deliver Satellite QKD
- Additionally – close relationship with Toshiba on terrestrial QKD
- Other activities include ongoing Penetration Testing / Assurance, Standardisation, Key Management, Overall system integration (Ethernet etc)

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First commercial trial of QKD and Industry 4.0

- How to design a QKD-secured data link between two NCC buildings
- Using all commercially available products, including the fibre access
  - Toshiba QKD solution – carefully designed for working alongside classical channels
  - Adva ethernet transmission solution – 10GE with external key input feature
  - Openreach OSA filter connect fibre product – provides managed access to 8 / 16 channels of optical spectrum

NCC – National Composite Centre based in Bristol
https://www.nccuk.com/

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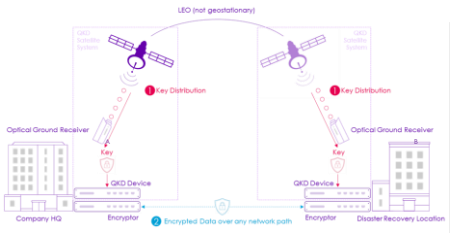
Satellite delivered Quantum Key Distribution (SQKD)



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What is it?

- **A means of providing encryption keys anywhere on the planet:**
  - The satellite transmits raw key material to the Optical Ground Receivers (OGRs) using individual photons;
  - Satellite and OGRs agree which bits get used to construct the keys stored at each OGR;
  - The second OGR also receives information to enable it to securely reconstruct the keys supplied to the first, thus enabling secure communications between them.

Status

- **All system elements in progress:**
  - European Space Agency (ESA) is co-funding the design, construction and launch of the first satellite and associated ground control;
  - Innovate UK is co-funding the development of low-cost OGRs;
  - Innovate UK is co-funding development of 2nd generation satellite technology and creation of UK supply chain;
  - UK Space Agency is co-funding development of a "5-Eyes & Friends" government services system ("Federated Quantum System");

Timeline

- **System will be deployed through 2022/23:**
  - First Arqit satellite launched and ground control system in place: target end;
  - Second (improved performance, UK supply chain) satellite launched mid/late 2023;
  - Optional additional satellites would launch from late 2023 onwards.

ArQit and BT

- **UK-based Sat-QKD start-up company**
  - Recently gone public around LEO satellite plans
  - BT contract = National Master Distributor rights
  - Exclusive sales to any UK-HQ'd company
  - Connection to any global location
  - Reseller rights to ArQit Quantum Cloud – a new Sat QKD secured cloud service
  - Press Release issued in May 2021

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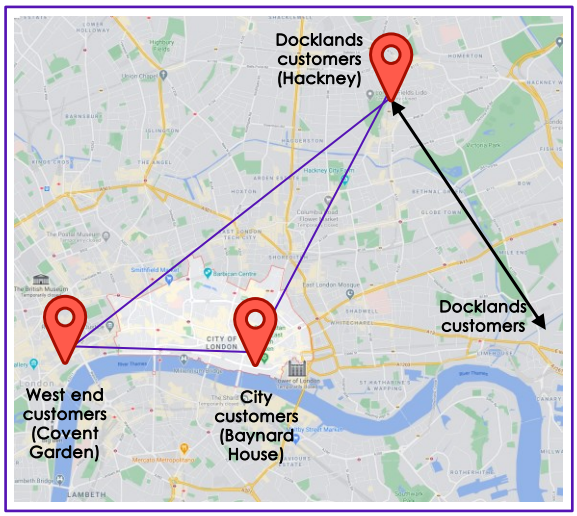
London metro trial to accelerate commercial QKD services

What:

- 2-3 year metro-based trial providing **ultimate secure connectivity**
- QKD technology provided by Toshiba
- 3 node ring with connections to Telehouse and Equinix
- Connections to 6 additional trial customer sites
- Evolution from trial to full commercial launch
- Fully integrated into BT Network Management system
- Satellite-ready allowing global quantum security

Why:

- Acceleration towards a terrestrial UK QKD commercial service with real customers
- Design and testing of potential commercial end to end products and services
- Validation of markets and early adopter use cases
- Asserts BT market



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Conclusions and further discussion

- 21st Century will turn out to be the century of photonics
- Amazing new applications will emerge that require enormous bandwidths and a fully integrated wireless + photonics + edge network
- Photonics will get more integrated, cheaper, open, plug and play
- Bandwidth growth will start to flatten (prediction which has always been wrong before!)
  - Limit to how much can be consumed by human beings due to our senses (eyes etc)
  - M2M will continue to drive growth
  - The flattening will be at a high level which will be too expensive to support unless photonics continues to innovate
- Photonics will start to eat into markets traditionally served by electronics
- Convergence of photonics and electronics will lead to a blurring of existing roles in
  - Electronics and photonics manufacturers
  - Operators and content providers
  - Research – groups, journals, conferences (OFC!)

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