Optoelectronics, a global telecom carrier's perspective

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Abstract

This paper summarises the current approaches to high speed optical transmission design. Cable & Wireless operates a large global optical transmission network, with the main purpose of serving the bandwidth market and of providing connectivity for its Internet Protocol data networks. In long haul spans, dense wavelength division multiplexed systems with aggregate capacities of 1 Tbit/s per fibre are deployed. The increase in bandwidth requirement is driving the need for more complex technologies that deliver a jump in system capacity. Emerging optoelectronic technologies are discussed, with particular focus on 40 Gb/s per wavelength transmission and optical wavelength switching.

I. Introduction

This paper is divided into five main sections. The Cable & Wireless optical network is briefly described to identify the requirement for high speed optical transmission systems. A brief review of optical fibre transmission impairments and dense wavelength division multiplexing (DWDM) is presented to assist the discussion of the merits of the approaches described. A statement of the status of 10 Gb/s transmission is followed by a discussion of two approaches to 40 Gb/s transmission. The final section examines aspects of the architectural development of optical switching.

There has been a surplus of transmission capacity in the early years of the current decade following the dot.com crash and telecom downturn. This was followed by a steady growth in the demand for bandwidth in the last 3 years, which is requiring upgrades to current systems and triggering the deployment of new technology.

II. Cable & Wireless Network

This section reviews the optical transmission network.

A. *Company historical highlights*

Cable & Wireless has its roots in the 1860s when undersea cables were first being deployed. A number of companies merged to become the Eastern Telegraph Company, which operated cables linking Britain internationally. In 1928 it was merged with Marconi Wireless to form Cable & Wireless and was nationalised in 1947. A new phase begun with privatisation in 1981 and was quickly followed by the award of a license to operate in the UK to compete with British Telecommunications under the Mercury joint venture. Since 2005 it has been effecting consolidation in the UK market with the purchase of Energis and Thus (in progress). The company has network presence in around 150 countries and is the incumbent in several ex-UK territories.

B. *Optical network services and global infrastructure*

The network covers the UK, continental Europe, Asia and the United States of America (EAUS division) and multiple in-country operations (the International division). Principal services are Internet Protocol (IP) virtual private networks, wholesale voice, managed hosting, IP peering (public Internet) and global bandwidth. Together these require high capacity optical networks.

The infrastructure on which optical networks are built varies with geographical area: in the UK, fibre ducts are owned and multiple DWDM systems are deployed per duct; in Europe, the East coast of the US and Singapore, leased fibre are used to deploy single DWDM systems; US, Japan and Hong Kong use lease wavelengths and leased sub-wavelengths are used in the rest of the world. Cable & Wireless has significant interests through joint ventures in several subsea cable systems, the most significant being the Apollo transatlantic cable system [1].

1) *Network architecture:*

Two principal layers, the packet layer and transport layer, extend from the customer site to the core nodes. In the packet layer a range of service types are demarcated on the Multiservice Platform device, which are connected to core IP Multiprotocol Label Switched routers. The transport layer has devices known collectively as Multiservice Provisioning Platforms that aggregate traffic and perform time domain multiplexing (TDM). These are connected to core devices called optical cross connects, which perform high granularity multiplexing and grooming. The optical transmission network serves the packet and transport layers at several stages as the traffic is aggregated.

C. *Deployed DWDM systems*

A useful way to look at the growth in capacity of DWDM systems is to look at how the product of the transmission capacity and distance between electrical regenerators has increased over time. This product is used because the number of wavelengths that can be deployed on a system generally decreases with the distance due to the build up of optical noise. Figure 1 shows a plot of deployed Cable & Wireless DWDM systems. This shows that the capacity-distance product has been doubling approximately every 18 months.

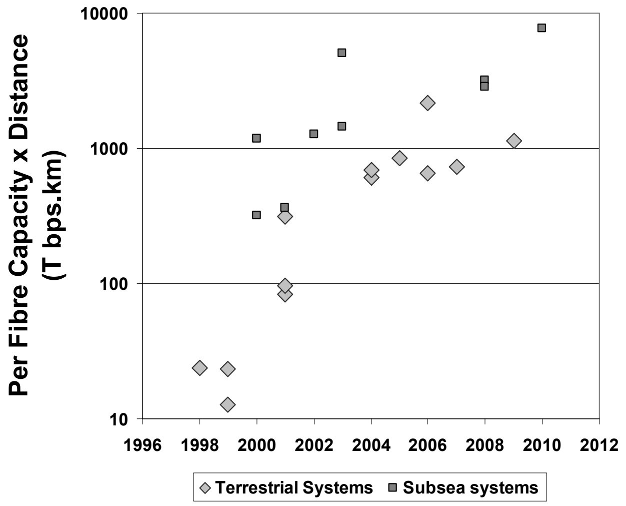

Figure 1: Cable & Wireless deployed systems. Subsea systems are joint ventures. The final point of each series is a planned system.

1) Typical system characteristics:

Current typical system characteristics can be summarised as follows: scalability to 100 or more wavelengths; un-electrically regenerated reach up to 2000 km; flexibility; power consumption ≤ 2 kW per 600mm by 600mm by 2.2 m rack with an expectation that a 1 Tb/s system should occupy around 2 racks.

Flexibility is important in three areas. Reconfigurability – this refers to the ability to change the wavelength point of entry to and exit from the DWDM system incorporated into devices known as Optical Add-Drop Multiplexers (OADM), which are described in section VI. Tunability – on the network side optical ports can be tuned to any of the typically 80 supported wavelengths. Such functionality minimises operational costs through reduced spares holding and supports rapid turn up of services. Pluggability – on the client side pluggable optics support a range of wavelengths and fibre types, which has the same benefits as tunability.

III. Optical Fibre Transmission and DWDM Review

Optical fibre transmission has developed rapidly over the last decade and recently many concepts from radio transmission have been borrowed and reinvented: however, transmission in single mode optical fibre is very different to radio transmission, since, the energy density leads to important nonlinear effects. This section reviews optical transmission and DWDM concepts, considering linear and then nonlinear impairments and DWDM principles.

A. *Linear impairments*

1) Attenuation

Attenuation in silica fibre [2] has a minimum due to intrinsic absorption between 800 nm and 1600 nm. In this region the loss profile is dominated by OH ion peaks and Raleigh scattering, which is proportional to the inverse fourth power of wavelength. The resulting profile is shown in figure 2. Attenuation minima are seen at 850 nm, used for intra-office connectivity, 1310 nm, used for inter-office connectivity and around 1550 nm, which is used for DWDM. The minimum attenuation in this region is around 0.18 dB/km. Raman and erbium-doped fibre amplifiers (EDFA) are used to mitigate attenuation. A typical gain of 25 dB is achieved with EDFA amplifiers leading to amplifier spacing of up to 100km. Raman amplifiers can be used to allow for wider amplifier spacing.

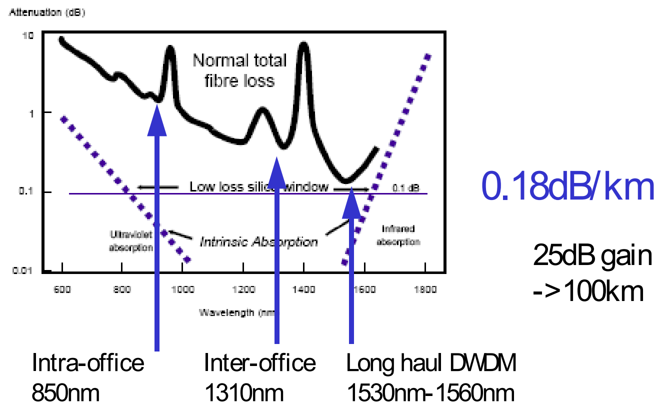

Figure 2: Attenuation is silica fibre [2].

2) Chromatic dispersion (CD)

The International Telecommunications Union (ITU) standardises fibres and two types are commonly deployed: G.652 has the dispersion zero near 1310 nm and dispersion of ~19 ps/nm.km at 1550 nm; G.655 is a non-zero dispersion shifted type with dispersion zero just below 1500 nm and dispersion of ~5 ps/nm.km at 1550 nm. At 10 Gb/s the bit duration is 100 ps: ~20 ps of dispersion can be tolerated. Dispersion compensating fibre is widely used.

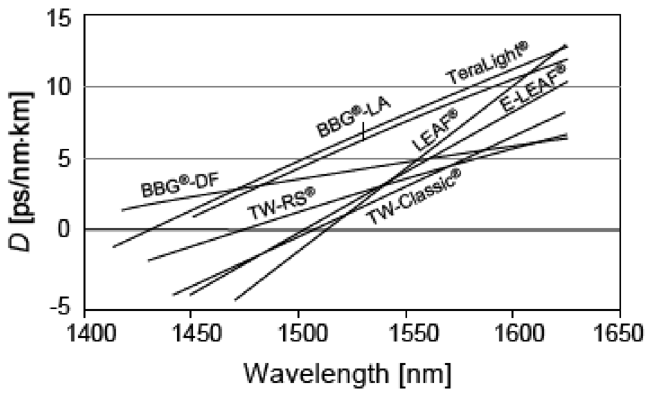

Figure 3: Attenuation in some non-zero dispersion shifted fibres [3].

3) Polarisation mode dispersion (PMD)

Polarisation mode dispersion is due to polarisation states propagating at different speeds due to physical imperfections in fibre. Typically better than 0.2 ps/√km but can be much worse. Generally it is not a problem for 10 Gb/s transmission but can be very significant for 40 Gb/s transmission speeds and above. Studies have been done on deployed fibre [4, 5]. Some correlation between year of manufacture and performance has been seen but no correlation between type of installation–either buried or in Overhead Power Ground Wire (OPGW)–and performance has been seen, as shown in figure 4.

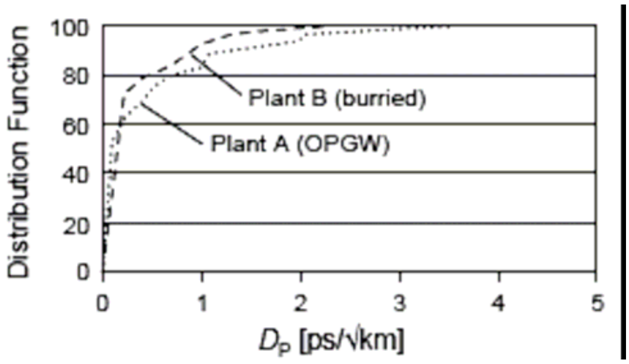

Figure 4: Dispersion in buried and overhead (OPGW) cables [4].

B. *Nonlinear impairments*

Many types of nonlinear impairments are considered by DWDM system designers, three of which are: self phase modulation, cross phase modulation and four-wave mixing. All are strongly dependent on the optical power density in the fibre and this leads to a trade off between better optical signal-to-noise ratio (OSNR) with increased transmit power and increased intersymbol interference through nonlinear effects as power is increased. The typical per channel transmit power is 2 dBm.

C. *DWDM review*

The basis of DWDM is the ability to multiplex closely spaced optical wavelengths. This multiplexing is commonly done with Arrayed Waveguide Gratings, which are fabricated as planar silicon devices. Multiplexing is often done in two stages, although designers chose different values for the ratio between stages.

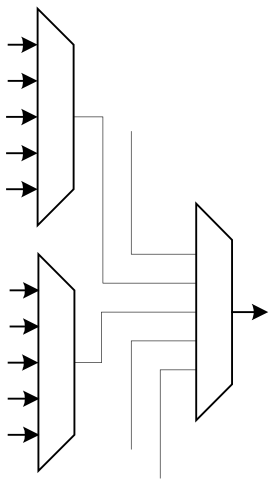

Figure 5: Two stage optical multiplexing scheme.

The wavelength spacing has been defined by the ITU in standard G.694.1. Channels are referenced to a frequency of 193.1 GHz. The commonly used C band and EDFAs yield in excess of 80 wavelengths with 50 GHz spacing.

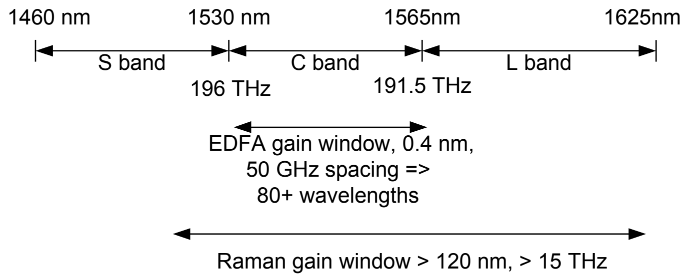

Figure 6: Transmission bandwidth and amplifier gain windows.

IV. 10 GB/S TRANSMISSION

A. *Current industry standard*

The 10 Gb/s transmission speed has become the industry standard. A typical transmitter uses a continuous wave laser, external modulator, which is an electroabsorption positive-intrinsic-positive (pin) or Mach-Zehnder lithium niobate ($LiNbO_3$) device. An On/Off Keyed (OOK) Nonreturn-to-Zero (NRZ) format is almost universally used. Receivers are usually avalanche photodiodes. For flexibility full C band tunability with 50 GHz increments on the DWDM side and pluggable client side for variable reach and wavelength (850/1310/1550 nm) is common. A typical power consumption is 35W per transceiver with client and network side optics.

Forward Error Correction (FEC) [6] has been standardised in ITU recommendations G.975 and G.709, specifying a Reed-Solomon scheme with 7% overhead. Both standards-based and proprietary schemes have been adopted by system vendors and this is crucial in extending the reach, which in many systems is more than 2000km.

Reconfigurable intermediate node add/drop to/from either direction (2 degree ROADM) has been available and deployed. This technology is developing rapidly and is discussed in section VI.

B. *Alternative approaches*

A number of alternative approaches are worth noting.

1) *Full electronic dispersion compensation*

This is achieved through digital signal processing and can fully compensate for the dispersion over the full length of the optical path [7], which can save up to 15% on transit delay. The disadvantage is that such an optical network is closed since it cannot accept wavelengths without this technology built in. While not widely deployed at 10 Gb/s this technique is likely to be important for 100 Gb/s solutions.

2) *Return-to-Zero (RZ) and Solitons*

Pulses shorter than the full bit period can have beneficial transmission properties; the added complexity, however, has prevented wide scale deployment. These techniques may also feature in high speed solutions beyond 10 Gb/s.

3) *Advanced amps (Raman)*

Raman amplifiers offer two distinct advantages in increasing the viable distance of a single span, and widening the amplification bandwidth. This has been used by Xtera to increase the 10 Gb/s wavelength count to 240 in a single system.

4) Photonic integrated circuits

Photonic Integrated Circuits (PIC) on indium phosphide (InP) chips have found commercial success. Infinera has developed a PIC with 10×10 Gb/s transmitters or receivers and multiplexers on a chip: cheaper, more frequent, regeneration avoids impairments by reducing regeneration spacing and also enables fast service turn up once the PIC has been installed.

V. 40 Gb/s Transmission and Beyond

The deployment of 40 Gb/s has been delayed several years by the economic climate that has affected severely telecommunications and Internet-based technology development. Transmission at 40 Gb/s is, however, now ready for deployment and is being adopted in significant quantities.

A. *40 Gb/s clients*

High-end IP routers are the main potential users of 40 Gb/s. Tb/s routers operating at 10 Gb/s would require many parallel links. This causes problems of load sharing, large routing tables, management complexity and power consumption. The solution to this would be to use 40 Gb/s and then later 100 Gb/s.

Modules that perform a 4:1 TDM combiner function to 40 Gb/s are proving to be a strong driver for 40 Gb/s in optical networks since the spectral efficiency is increased compared to discrete 10 Gb/s modules. This is in contrast to the situation at 10 G/bs where the deployment of 4:1 combiners working at 10 Gb/s network side with 2.5 Gb/s clients was not widely deployed until several years after the first 10 Gb/s client was ready.

B. *System requirements*

Any candidate 40 Gb/s solution should be deployable with existing DWDM systems to maximise the investment. Link engineering rules–amplifier gain and spacing, attenuation budgets, chromatic and polaristation mode dispersion values and 50 GHz filtering–will be the same and the 40 Gb/s stream must be able to coexist with deployed 10 Gb/s. 40 Gb/s compared to 10 Gb/s has a CD tolerance 16 times worse and PMD tolerance 4 times worse for the same modulation format.

C. *Modulation formats*

There are four ways to modulate the optical field in an optical fibre: intensity, frequency, phase and polarisation [7]. These are illustrated in figure 7. NRZ OOK used for 10 Gb/s. There are auxiliary modulation features that may be used. Frequency and polarisation modulation have had little focus due to inherent difficulties, whereas phase modulation has produced a rich set of solutions that continue to be investigated. Some important formats are represented in figure 8. Two particular solutions will be discussed in more detail to illustrate the component complexities and relative transmission advantages: duo-binary (DB), an intensity modulation format with phase as an auxiliary modulation, and differential phase shift keying (DPSK), a phase modulation format.

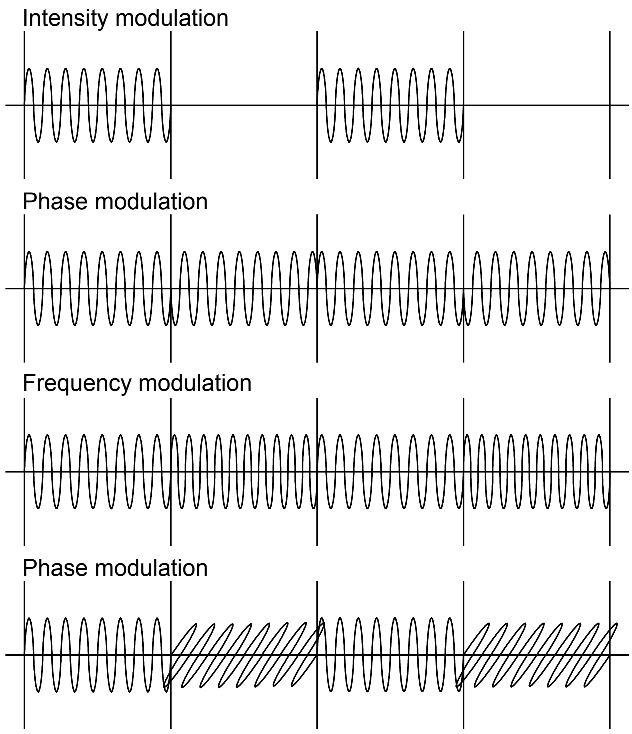

Figure 7: Possible modulation formats.

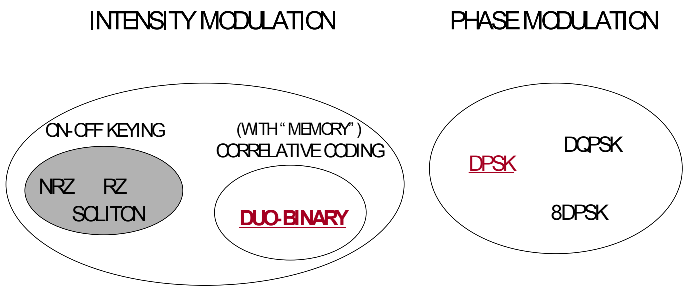

Figure 8: Modulation formats grouped by modulation type.

D. *Duo-binary (DB)*

Duo-binary belongs to a group of correlative coding formats in which there is a correlation between the data and the phase of the transmitted signal. Figure 9 shows the data, amplitude and phase relationship. Whenever there is an odd number of 0-bit levels between 1-bit pulses then a change of phase occurs. This has advantages both in the time domain and frequency domain that lessens the effect of chromatic dispersion. In the time domain, if two 1-bit pulses spread into each other they will interfere destructively thus preserving the low 0-bit level in between. In the frequency domain the spectrum is narrowed due to the smoother +1 0 -1 transitions between consecutive 1-bit pulses. Both these behaviours improve chromatic dispersion tolerance.

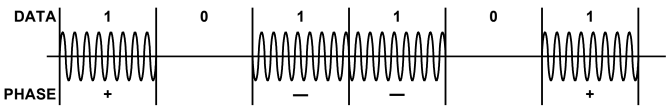

Figure 9: Duo-binary data, amplitude and phase relationship.

1) Duo-binary optoelectronic components

The optoelectronic block diagram is shown in figure 10. NRZ data is precoded such that there is a level change for every 0-bit in the original data. The encoder is a severe low pass filter, which feeds a Mach-Zehnder modulator. Both the precoder and encoder are additional electronic components needed compared to NRZ OOK. The receiver is the same direct detection method used for OOK.

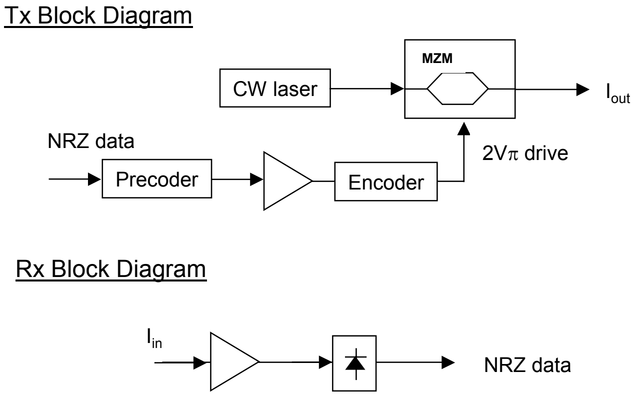

Figure 10: Duo-binary optoelectronic block diagram.

E. Differential phase shift keying (DPSK)

In DPSK the NRZ data is converted to phase encoding such that a 1-bit level leads to a π phase change. The data and phase relationship is shown in figure 11.

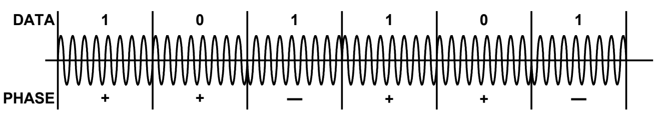

Figure 11: DPSK data and phase relationship.

1) DPSK optoelectronic components

The optoelectronic block diagram is shown in figure 12. The same encoder as for DB is used but there is no need for the encoder. The receiver design is significantly more complex. Tunable dispersion compensation is required as the spectrum is broader resulting in lower chromatic dispersion tolerance. A delay and add MZI feeds a balanced receiver to recover the NRZ data. These three stages represent additional high-cost optical components compared with NRZ OOK and DB modulation.

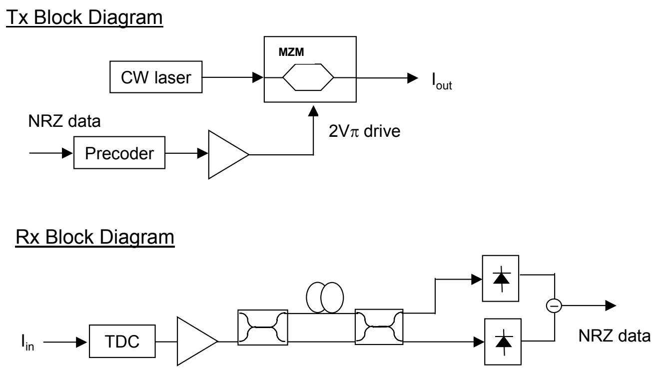

Figure 12: DPSK optoelectronic component block diagram.

F. Comparison of modulation formats

Table 1 compares the qualities of DB and DPSK formats discussed above. While DPSK is more expensive, its reach performance combined with lowering costs as economies of scale appear should promote wide deployment.

Table 1: Comparison of DB and DPSK performance compared to NRZ OOK at 40 Gb/s

	DB	DPSK
OSNR	–	++
CD tolerance	++	+
PMD tolerance	Similar	+
Nonlinearity	Similar	+
Cost and complexity	Similar	–
Reach	1000 km	1600 km

G. 100 Gb/s

There is a clear driver for Ethernet connectivity at around 100 Gb/s. Standardisation is in progress–but not completed–and many research papers report results at around this bit rate. Compatibility with current deployed systems is preferred and a field trial of mixed speeds has been undertaken [9]. An example of the approach is shown in figure 13 [10]. The modulation format shown here is polarisation-multiplexed quadrature phase shift keying (PM-QPSK). It is immediately evident that the complexity has increased substantially and the inclusion of digital signal processing (DSP) should be noted.

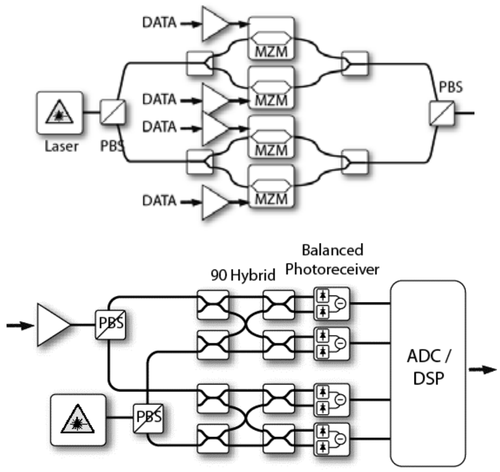

Figure 13: Optoelectronic block diagram for 100 Gb/s Polarisation-multiplexed QPSK.

VI. Optical Switching

DWDM systems have evolved from basic point-to-point formats to include fixed, and then reconfigurable, optical add-drop multiplexing (OADM) functionality. The drivers for this development are to remove costly optical-electrical-optical (OEO) regeneration and to increase speed of provisioning and flexibility. Extending this to a fully functioning optical wavelength switching node [11] would reduce operational and capital expenditure and increase flexibility with all the accompanying planning, provisioning, resiliency and redeployment benefits.

1) Optical add-drop Mulitplexer (OADM)

OADM nodes were introduced first incorporating fixed filters that allowed access to a part of the band. Figure 14 shows a schematic for the functionality; only one of the two directions is shown for simplicity.

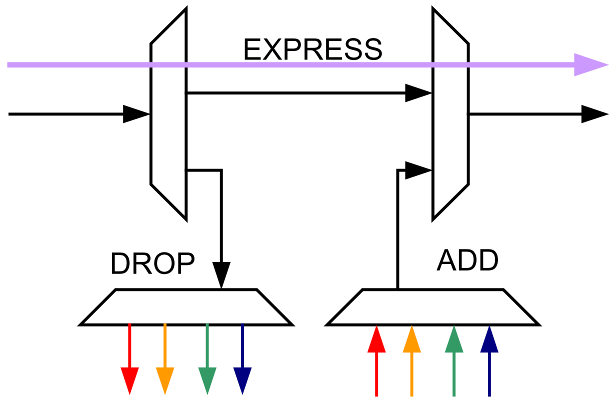

Figure 14: OADM block diagram. A single direction is shown for simplicity.

2) ROADM, 1st Generation

Reconfigurability has been added to OADM with the addition of a splitter and wavelength blocker as shown in figure 15. The purpose of the blocker is to remove the wavelengths that are dropped so that wavelengths can be added without interference from the express path. Blocker technology is relatively mature, micro electromechanical systems (MEMS), liquid crystal and planar lightwave circuits (PLC) being the principal solutions. Wavelength equalisation is often incorporated in the blocker.

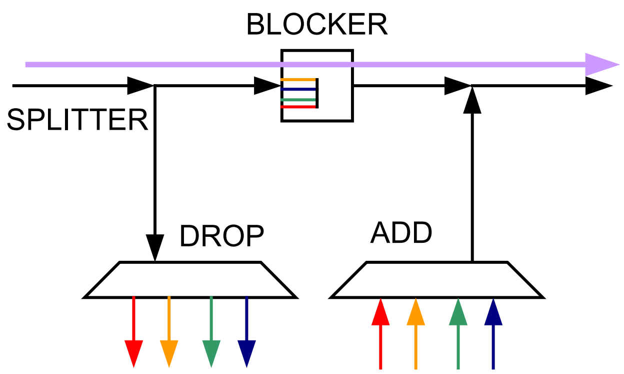

Figure 15: ROADM with blocker

3) Blocker scalability problem

ROADMs using blockers run into a problem as the number of directions (degrees) increase because the number of blockers required scales as n^2-n and this makes their use impractical beyond 3 degrees. Figure 16 illustrates the problem.

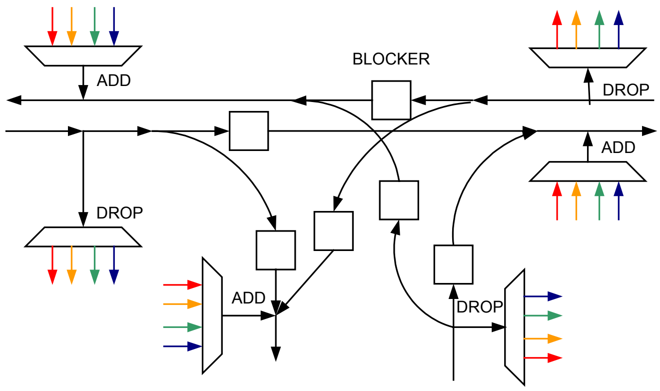

Figure 16: Three degree node illustrating requirement of six blockers.

4) Wavelength Selective Switch (WSS) ROADM, 2nd Generation

A solution to this blocker scalability problem is to use a wavelength selective switch (WSS) as shown in figure 17. The number of WSS devices scales linearly with the number of degrees. A WSS can switch any of the served wavelengths from an ingress port to any of its egress ports. Typical port counts are 1 ingress and 9 egress (1×9). WSS technology is relatively immature. MEMS are widely used but also liquid crystal and piezoelectric beam steering solutions have been developed. 100 GHz spaced optical grid with 40 wavelengths is typical but 50 GHz spaced grids are expected to come to market soon.

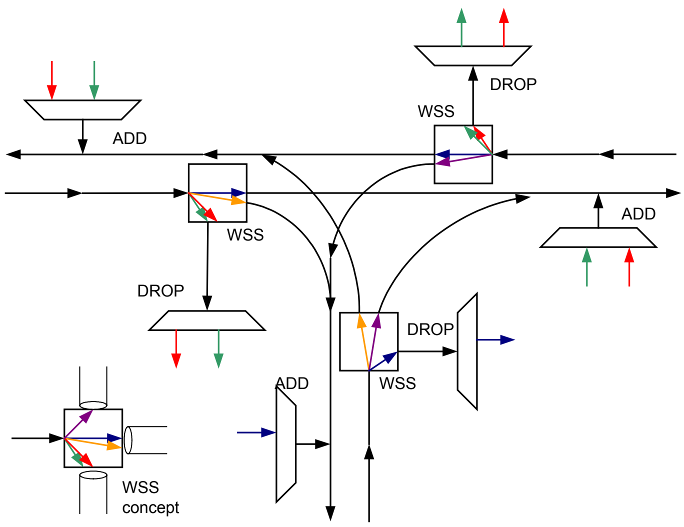

Figure 17: ROADM using WSS devices. A wavelength can be switched from the ingress port to any of the egress ports.

The combination of 50 GHz WSS technology and a 40 Gb/s transmission rate is promising to extend significantly the capacity and flexibility of optical networks in the next three years.

VII. SUMMARY

The Cable & Wireless network has been used to illustrate the role of optical networks and to make the case that there is a driver for higher bandwidth and more flexible optical transmission systems. 10 Gb/s DWDM system design is mature and 40 Gb/s is ready for deployment. Two 40 Gb/s design solutions have been described and the merits compared. The development of wavelength selective switches is enabling flexible reconfigurable networks. The prospect of being able to deploy 40 Gb/s DWDM systems with multi-degree ROADMs over the next three years is an exciting one for national and global carriers.

VIII. ACKNOWLEDGMENTS

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