White Paper

A comparison of next-generation 40-Gbps technologies

There are many proposed optical transmission systems which offer 40-Gbps/wavelength capacity. The unbridled adoption of these solutions may well depend on the degree to which they overlay on existing dense WDM 10-Gbps links. This paper provides a description of new 40-Gbps technologies being proposed and reveals their true compatibility with existing 10-Gbps infrastructure.

Introduction

Today's photonic network is evolving towards greater path and wavelength agility as well as lower cost through operational simplicity. The result of this evolution will be an Adaptive All Optical Intelligent Network.

- **Adaptive** — A network that can be easily reconfigured to meet continuously changing end-user demands.
- **All Optical** — A network with minimal Optical-Electrical-Optical (OEO) regeneration points for increased simplification and reduced costs.
- **Intelligent** — A network with the ability to monitor and automatically adjust for aging and changes in operating conditions to ensure continual optimal signal performance.

Key building blocks in delivering this vision, as illustrated in Figure 1, include Reconfigurable Optical Add/Drop Multiplexers (ROADMs) for network flexibility and service agility, electronic dispersion compensation technology for a simpler photonic line, and tunable lasers and filters to eliminate the need for truck rolls and reduce sparing costs. The value that ROADMs and electronic dispersion compensation technology bring to the network is described in more detail below.

Reconfigurable Optical Add/Drop Multiplexers (ROADMs) give network operators business plan tolerance and agility, allowing them to react quickly to changing customer and service requirements. A ROADM must be able to provide multiple branching capabilities so that wavelengths can be added, dropped or re-routed across the network with complete flexibility and ease. A ROADM must be able to operate in 50-GHz networks for maximum scalability, as well as in 100-GHz environments for cost-sensitive applications. A final critical element of a ROADM is the ability to transport any traffic capacity, whether it be at 10 Gbps, 40 Gbps or 100 Gbps.

Another key building block for an Adaptive All Optical Intelligent Network is electronic dispersion compensation technology. Using digital signal processing

Figure 1. Adaptive All Optical Intelligent Network

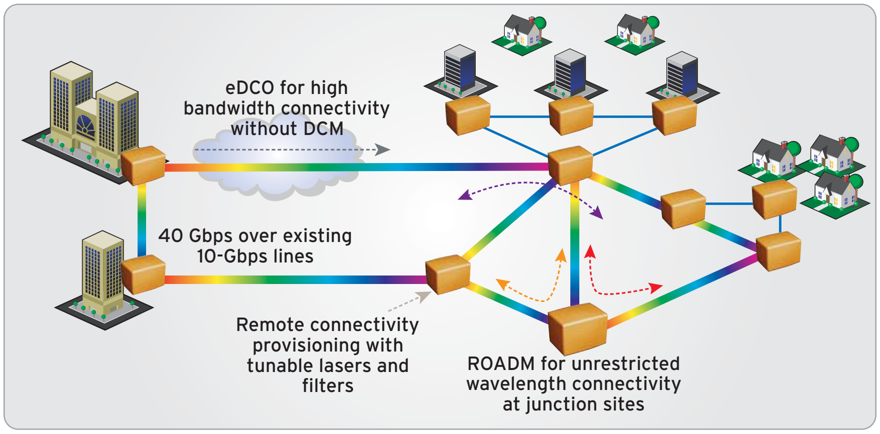
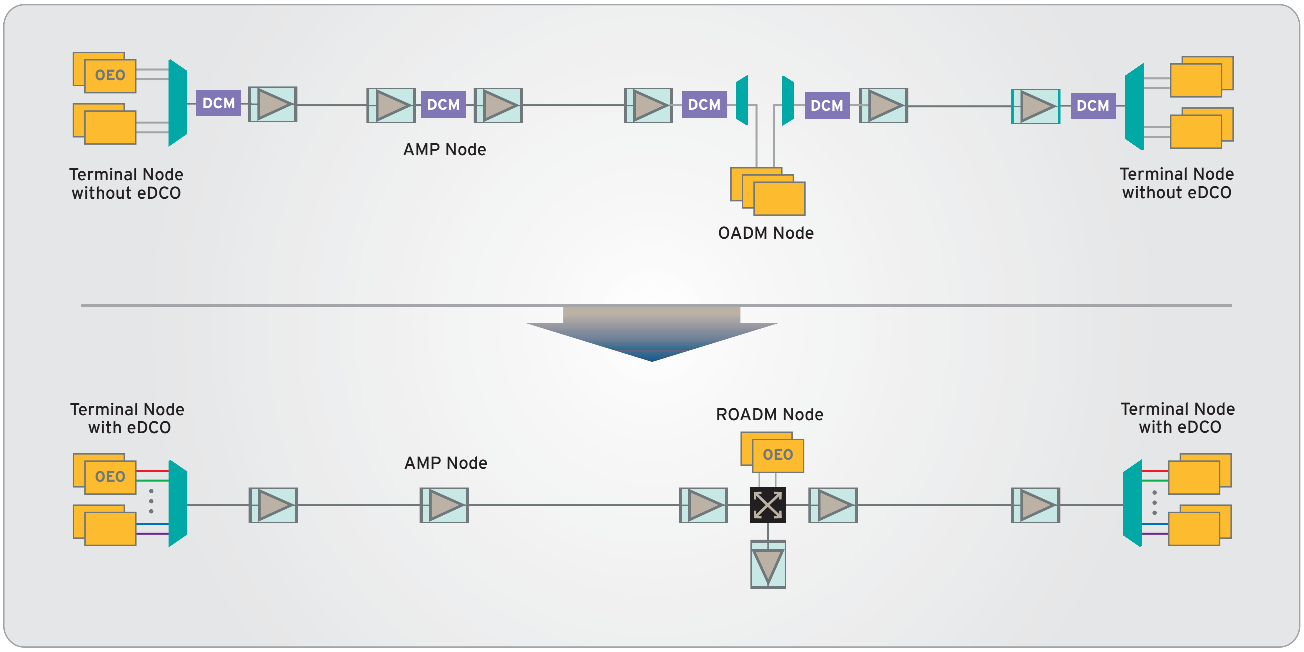


Figure 2. Network simplification with eDCO and ROADM



in the terminal equipment to compensate for optical impairments in the line has become a very successful technique in simplifying photonic networks, as has been proven with Nortel's electronic Dynamically Compensating 10G Optics (eDCO) that were introduced in 2005. eDCO extends wavelengths over 2000 km without requiring any dispersion compensation equipment. eDCO not only removes the cost associated with the Dispersion Compensation Modules (DCMs) and their associated amplifiers, but it also greatly increases the agility of the network. Much of the fiber characterization and network engineering that was previously required is no longer needed. Operators no longer have to worry about what compensation is required depending on which fiber their wavelengths are traversing; all the compensation is done automatically by the electronics in the transceiver. With eDCO, service providers can fully leverage the agility offered with ROADM and be able to reconfigure the network and switch wavelengths without having to re-engineer any dispersion maps.

The network simplification that is achieved with eDCO and ROADM is depicted in Figure 2.

Considerations when evolving to a higher capacity network

When evolving the network from 10G to 40G, and in the future to 100G, the selected solution must continue to meet the objective of delivering an Adaptive All Optical Intelligent Network. To be more precise, for the higher rate solution to be volume deployable, the following criteria must be met:

- Have similar deployment and operational conditions as the current system, despite Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD) and Optical Signal-to-Noise Ratio (OSNR) constraints
- Be scalable, i.e., support 50-GHz spacing
- Maintain complete agility required to meet ever-changing service requirements (ROADM flexibility)
- Be cheaper than today's equivalent capacity solution (i.e., 40G must be cheaper than 4x10G)

Challenges present with 40G networks

The delivery of a 40G transport solution using a TDM approach does not meet the criteria for a widely deployable solution.

There are three key challenges inherent with 40G solutions available today. To attain four times the bandwidth, the signal in a 40-Gbps TDM solution has four times the baud rate (bit interval reduced from 100ps to 25ps). This implies that four times less light per bit is entering the receiver, and results in an OSNR impact of 6dB. It also results in CD sensitivity being worsened by a factor of 16 and PMD tolerance being worsened by a factor of four. These challenges result in a severe toll on the reach of the system and impact the economics of the solution.

In addition to the reach impact mentioned above, 40G solutions based on TDM approaches are severely impacted by the presence of optical in-line filters. These filters are employed in both OADMs and ROADMs, which are deployed extensively in modern optical networks. This constraint will have an impact on the type of routes where 40G may get deployed, and implies that 40G TDM may not be suitable in OADM-rich environments such as metro and regional networks.

A comparison of commercially proposed 40G technologies

Several modulation schemes have been proposed as a basis for delivering next-generation 40G systems: Duobinary, Differential Phase Shift Keying (DPSK) and Differential Quadrature Phase Shift Keying (DQPSK).

10G reference system

Most of the 10G systems today use NRZ (Non-Return-to-Zero) as the standard modulation transmission format. With this technique, light is switched on and off to encode binary low and high states, represented by numerals 0 and 1, and the resulting signal is transmitted over fiber. These systems can be equipped with high gain Forward Error Correction (FEC), yielding reach in excess of 1000 km. This is the system used as a reference throughout this paper. All the performance statements and comparisons will be concluded with respect to this system.

Duobinary

Duobinary modulation (also called Phase Shaped Binary Transmission, or PSBT) changes the phase of the optical signal of each "1" bit for a certain sequence of bits and reduces the average optical signal power by one half compared to standard NRZ signals. Due to the phase coding, the optical bandwidth of the signal is reduced, which leads to improved chromatic dispersion and PMD tolerance over 40G NRZ. The performance of a Duobinary solution, however, is still considerably inferior to a 10G NRZ system, as is pointed out in Table 1.

Differential Phase Shift Keying (DPSK)

DPSK (Differential Phase Shift Keying) codes the bit information into the phase of the optical signal. This technique provides a 3dB higher OSNR sensitivity than Duobinary modulation, which roughly doubles the reach performance compared to a Duobinary solution. To obtain the best system performance, the phase encoding needs to be detected in the receiver using a balanced detector (2 PIN diodes) preceded by a 1 bit optical delay line. These components increase the cost of the receiver with respect to that of the 40G NRZ. It provides significant performance enhancement over 40G NRZ but still falls notably short of that of the 10G reference. Moreover, the impact of OADMs on the system reach is significant with the DPSK solution, as will be explained in more detail in the succeeding sections.

Table 1. Comparison of next-generation 40G systems

	10G NRZ Reference system	Duobinary	DPSK	DQPSK
Normalized reach	1	.4	.8	.65
CD tolerance [ps/nm]	+/- 500	+/- 90	+/- 90	+/- 200
PMD tolerance (<DGD>) [ps]	15	3.5	3.5	7
50-GHz filter/ OADM tolerance [# of OADMs traversed]	>16	3	3	3
100-GHz filter/ OADM tolerance [# of OADMs traversed]	>16	8	8	8

Note: All system specifications mentioned above are using the same end of life margin.

Differential Quadrature Phase Shift Keying (DQPSK)

DQPSK (Differential Quadrature Phase Shift Keying) is the four-level version of DPSK. In each symbol transmitted with DQPSK, two bits are encoded (bit combinations being 00, 01, 11 and 10). DQPSK has an additional advantage over DPSK in that it reduces the line rate by 50 percent, thus operating at 20GBaud. Conversely, this is obtained by adding significant complexity and cost into the receiver. The receiver needs double the amount of high speed opto-electronic components as the DPSK solution and roughly four times the amount of 40G NRZ. The key advantage to DQPSK is that components operate at half the frequency of those of a Duobinary solution. In addition, this system requires that two 1-bit optical delay lines be employed (one more than in the DPSK case). The significant improvement provided by this modulation method is the improved resilience to PMD with respect to the 40G TDM solution.

Operation over existing 10-Gbps networks

Reach

With respect to reach, all modulation schemes described perform worse than typical 10G systems today.

Of these methods, Duobinary is the most impacted when comparing its reach to that of 10G systems. Reaches of 500km are typical before electronic regeneration is required. Raman pre-amplifiers can be inserted to increase the reach, although these will significantly increase the network cost of the solution as well as complicate the system installation and operation.

CD and PMD tolerance

All three solutions have comparatively poor CD and PMD tolerance inferior to that of 10G NRZ. Because it operates at half the transition rate of the other TDM solutions, DQPSK has a better tolerance to PMD than either Duobinary or DPSK. It should be noted, however, that DQPSK PMD tolerance is still half that of a 10G NRZ system. PMD compensators, per sub-band of wavelength tweaking DCMs and tunable CD compensators can be deployed to improve performance, but, even with these remedies, performance parity with 10G NRZ is elusive. Moreover, the additional equipment that needs to be installed further impacts the economics of these 40G systems, as well as their ability to be easily reconfigured.

50-GHz wavelength grid compatibility

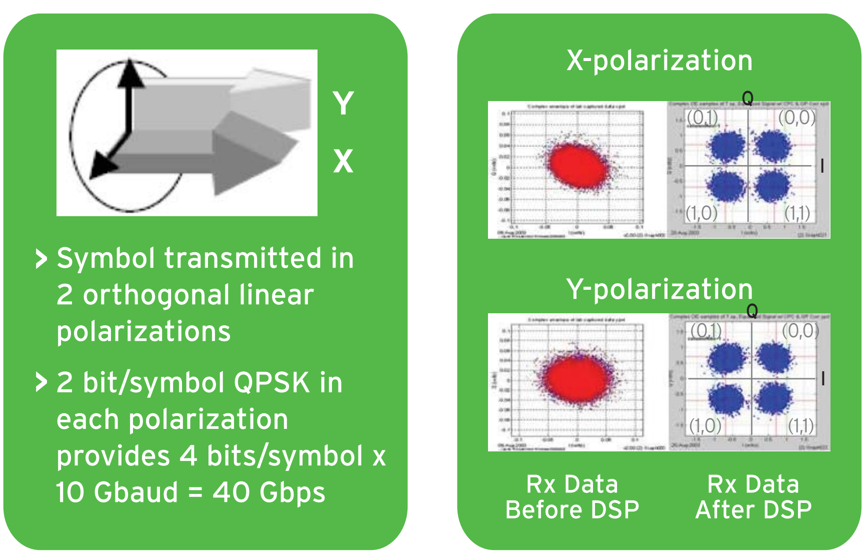
Duobinary, DPSK and DQPSK solutions can operate in 50-GHz systems, but all severely limit the number of OADMs/ ROADMs per span (to three) before regeneration is required. This restriction prevents service providers from re-using their existing architecture, and prevents them from benefiting from the agility and cost savings brought by ROADMs in the network.

Electronic implementation

The electronics in Duobinary, DPSK and DQPSK systems need to operate at higher frequencies than those employed in 10G systems. Because of this factor, these solutions are presently more expensive than 4x10G solutions, making them deployable only for niche applications. Moreover, this factor limits the procurement of suitable components to a select few number of suppliers, further impacting the relative economics of these solutions to current 10G systems.

To summarize, 40G Duobinary, DPSK and DQPSK solutions cannot be easily deployed over existing 10G networks due to the following limitations:

Figure 3. Dual Polarization Quadrature Phase Shift Keying



- Inferior reach to 10-Gbps systems, forcing Raman amplifiers into the network
- Inferior CD/PMD tolerance to 10G systems, forcing additional external compensation equipment
- Significantly different OADM/ ROADM tolerance than 10G systems with a difficult or impossible path to 50-GHz OADM/ROADM compliance

Introducing a volume deployable 40G solution

Dual Polarization Quadrature Phase Shift Keying (2-POL QPSK)

Nortel is solving the challenges of 40G transmission by using QPSK encoding at 10GBaud. Two QPSK signals are employed in this solution, as depicted in Figure 3. Each QPSK signal is modulating one of the two orthogonal polarizations of a single optical carrier. This method is called dual polarization (2-POL) QPSK. With this modulation technique, 40G transmission can be achieved using 10G-like electronic and optoelectronic components, and optical impairments will be equivalent to those in a 10G system. The receiver employed in this solution is a fully coherent receiver; the incoming signal is mixed with a local oscillator and then detected. A coherent receiver preserves the necessary characteristics of the signal to allow the QPSK decoding to be effected successfully. After high-speed and high-resolution analog to digital conversion, the signals are discriminated against and tracked using a unique, dynamic, high-speed digital, CMOS-based signal processor developed by Nortel.

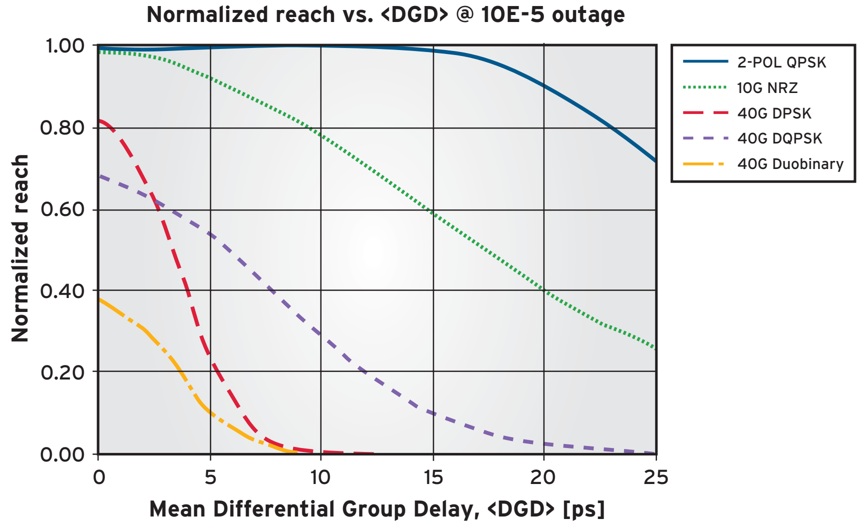
This proposal delivers significant benefits. First and foremost, superior optical performances, similar to those of a 10G system, can be achieved using this solution. Secondly, the digital signal processor (DSP) developed by Nortel enables full electronic CD compensation up to +/- 50,000ps/nm. Moreover, this method is also conducive to compensation of PMD and PDL to levels not achievable even by 10G systems. Another important factor is that 2-POL QPSK is fully compatible with supporting a series of several 50-GHz based OADMs/ ROADMs with 10G-like penalties. Finally, because this solution creatively uses 10G components, sourcing of the key components is very competitive, with numerous vendors available.

The innovation behind 2-POL QPSK is in line with earlier DSP-enhanced 10G systems proposed by Nortel (10G eDCO), burying optical complexity in a CMOS DSP processor and delivering significant network simplification to service providers.

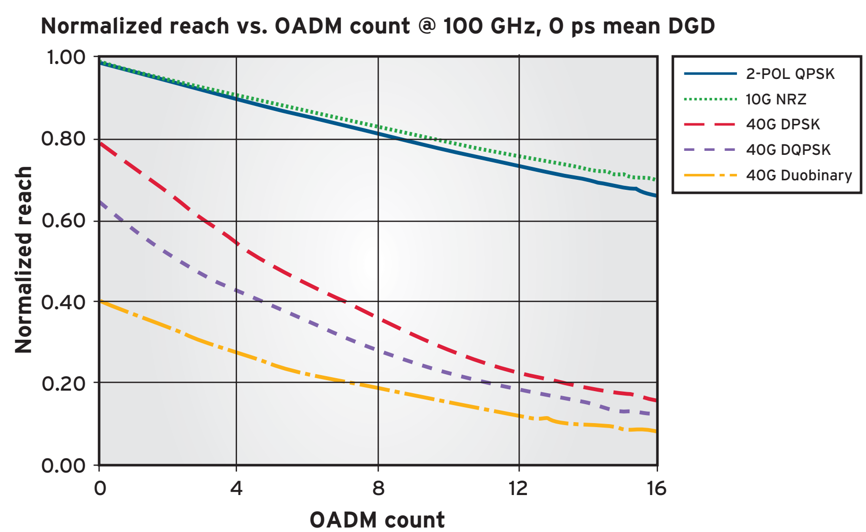
System performance

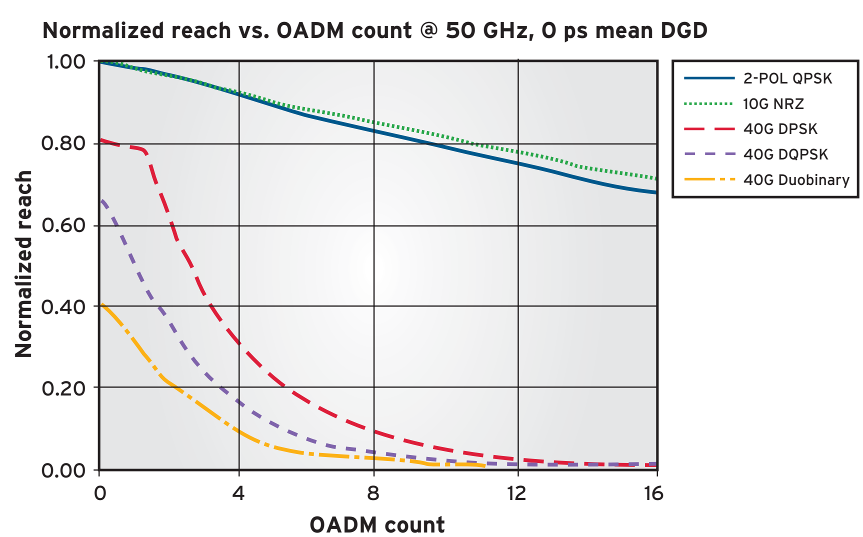
As illustrated in Figure 4, the 2-POL QPSK system, as proposed by Nortel, delivers superior tolerance to PMD with the tolerance even greater than that of a 10G system. The figure also demonstrates that 40G TDM systems are severely impacted by PMD, as expected. The enhanced resiliency provided by 2-POL QPSK enables network operators to significantly increase the value of their outside plant, since 40G transmission is now possible in locations where previously only 2.5G transmission could operate. This factor, coupled with the full electronic CD compensations delivered in the Nortel solution, removes all of the complexity associated to date with 40G transmission.

Figure 4. Normalized reach impact caused by PMD using different 40G implementations



Figures 5 and 6. Normalized reach impact caused by OADMs comparing different 40G implementations





Another benefit delivered by the Nortel 2-POL QPSK system is that it has the same spectral occupancy as a typical 10G system. Therefore, it behaves in a similar way to a 10G system with respect to OADM and ROADM concatenation. As shown in Figures 5 and 6, the reach allowed by the Nortel 2-POL QPSK is similar to that of a 10G system as the number of OADMs increases. Moreover, it has similar behavior even if the OADM is 50-GHz based. This is in sharp contrast to the other proposed 40G solutions that become impractical after a few OADMs.

As mentioned above, the Nortel 2-POL QPSK system delivers full electronic CD compensation up to +/- 50,000ps/nm (the same capability as the Nortel 10G eDCO). This capability frees up the system of all dispersion compensation limitations and allows it to fully leverage the reconfigurability benefits brought by ROADM. The Nortel 2-POL QPSK solution preserves and enhances this important networking value.

Nortel has designed and implemented digital signal processing (DSP)-enhanced electro-optics to simplify 10G and 40G networking. The same philosophy will be used to maintain similar line and system attributes for 100-Gbps transmission.

Table 2. Nortel's 2-POL QPSK with other comparison of next-generation 40G systems

	10G NRZ Reference system	Nortel 2-POL QPSK	Duobinary	DPSK	DQPSK
Normalized reach	1	1	.4	.8	.65
CD tolerance [ps/nm]	+/- 500	+/- 50,000	+/- 90	+/- 90	+/- 200
PMD tolerance (<DGD>) [ps]	15	25	3.5	3.5	7
50-GHz filter/ OADM tolerance [# of OADMs traversed]	>16	>16	3	3	3
100-GHz filter/ OADM tolerance [# of OADMs traversed]	>16	>16	8	8	8

Note: All system specifications mentioned above are using the same end of life margin.

Summary

The Nortel 2-POL QPSK solution meets and exceeds all the criteria of a volume deployable 40G solution and fully aligns with the vision of an Adaptive All Optical Intelligent Network:

- Requires **NO** disruption to the existing network:
  - Significantly superior CD tolerance to 10G networks, with integrated electronic dispersion compensation technology, eliminating the need for DCMs
  - Better PMD tolerance than 10G networks, eliminating the need for external PMD compensators
  - Equivalent Optical Signal-to-Noise Ratio (OSNR), eliminating the need for Raman amplifiers
  - Is scalable and can operate in 50-GHz-spaced systems
- Maintains complete agility required to meet ever-changing service requirements with flexible OADM/ROADM support
- Is less expensive than 4 independent 10G signals

Table 2 summarizes the technical superiority of the 2-POL QPSK solution with respect to other proposed offerings.

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