

Next-generation Electro-Optics Technology with Coherent Detection

Addressing the Challenge of Capacity Growth in Optical Networks

With aggregate bandwidth demand continuing to increase, driven by Web 2.0 with the emergence of new IP-based video and multimedia applications, network service providers are seeking ways to scale the capacity of their transport network at the lowest possible total cost of ownership (TCO) while maintaining network reliability and quality of service. The migration of line speeds from 10 Gb/s to 40 Gb/s and 100 Gb/s is becoming necessary, with the caveat that transmission performance is not degraded and that overall economics prove in. A significant part of the technical challenge is to design an electro-optics engine that can operate at 40 Gb/s and 100 Gb/s speeds over either existing or new fiber plant while achieving 10 Gb/s-like reach and performance without the need for external bulk dispersion compensation modules — without interfering with existing 10 Gb/s and 40 Gb/s signals and while consuming better than per-10 Gb/s amounts of space and power.

Alcatel-Lucent has created a next-generation electro-optics engine that leverages the concepts of optimized signal modulation coupled with coherent detection and builds on ultra-fast advanced digital signal processing (DSP) in CMOS in a very compact, space- and power-efficient design. This forms the heart of a 40G and 100G next-generation solution that provides outstanding transmission performance at a TCO that makes 40 Gb/s and 100 Gb/s transmission viable.

By combining the best transmission reach and dispersion tolerance, the highest resilience to linear and non-linear effects, the best compatibility with the huge bulk of conventional 10 Gb/s and 40 Gb/s channels in existing networks, and the best ability to achieve fast wavelength reconfigurations, the Alcatel-Lucent 40G and 100G next-generation coherent solution helps operators to easily deploy high-capacity networks and leverage their assets while lowering the cost per transported bit.

Table of contents

1	1. Modulation formats
1	1.1 Phase-domain modulation
1	1.2 Combining phase and polarization
2	2. Detection techniques
2	2.1 Differential detection
2	2.2 Coherent detection
3	3. Alcatel-Lucent next-generation coherent electro-optics technology for best-in-class 40 Gb/s and 100 Gb/s transmission
3	3.1 Overcoming fiber impairments for best performance
4	3.2 Existing network upgrades
5	3.3 Greenfield network deployments
5	4. Leading innovation and execution
6	5. References
6	5.1 Hero experiments and standardization leadership
6	5.2 Standards
6	5.3 Press releases
7	6. Contacts
7	7. Acronyms

1. Modulation formats

Today's wavelength division multiplexing (WDM) optical networks provide the transport capacity infrastructure for telecom services, and typically operate with wavelength line rates at 2.5 Gb/s and 10 Gb/s using traditional signal modulation format in the amplitude domain. However, as line rates increase beyond 10 Gb/s, fiber impairments such as chromatic dispersion (CD), polarization mode dispersion (PMD), optical noise and non-linear effects become very significant, severely impacting overall transmission performance and drastically affecting signal quality. For example, the impact of CD on a 40 Gb/s wavelength signal increases by a factor of 16 compared to a 10 Gb/s signal. In addition, the spectral bandwidth occupation of a 40 Gb/s signal is four times that of a 10 Gb/s signal, meaning fourfold the amount of noise that is detected at the receiver. This translates into a 6-dB penalty in optical performance for a given transmission power, or approximately four times less the distance that the wavelength can traverse in the network without electrical regeneration. As an additional consequence, utilizing for a 40 Gb/s signal the same modulation format traditionally used at 10 Gb/s results in reduced spectral efficiency, meaning fewer wavelengths can be transmitted down a fiber pair. These phenomena severely affect the performance of typical amplitude-shift keying (ASK) modulation formats with direct detection schemes that are conventionally utilized for 10 Gb/s wavelength transmission.

1.1 Phase-domain modulation

Overcoming these transmission impairments starts with a change in modulation formats. The use of modulation formats in the phase domain, or phase-shift keying (PSK) technique, becomes attractive for several reasons. Phase modulation schemes can provide better resilience against non-linear effects when compared to traditional ASK modulation because signal amplitude remains almost constant in time. In addition, phase modulation schemes become attractive as a means for lowering the overall effective transmission symbol rate (or baud rate), where multiple bits (that is, more information) are encoded per symbol; this means that the signal travels at a lower overall speed relative to its nominal 40 Gb/s or 100 Gb/s rate and, as such, it does not suffer the effects of increased PMD, CD or optical noise as outlined in the previous example.

Although phase modulation has definite advantages, phase modulation schemes do increase the complexity of the signal to the extent that there are now multiple signal states that need to be recovered by the receiver. In addition, when phase modulated signals are transmitted in a 50-GHz spectrum slot adjacent to existing 10 Gb/s signals, a non-linear phenomenon known as cross-phase modulation (XPM) occurs, which can severely impact overall transmission performance. As a result, phase modulated signals may incur incremental link penalties (that is, dB losses) to compensate for this. Alternatively, the signals may need to be separated in spectrum from the existing 10 Gb/s signals, with a significant waste of valuable optical spectrum.

Examples of phase-domain modulation formats for optical wavelength transmission are:

- Binary phase-shift keying (BPSK): a two-phase-state coding scheme
- Quaternary phase-shift keying (QPSK): a four-phase state coding scheme

1.2 Combining phase and polarization

To further increase the efficiency of the high speed signal, the two orthogonal polarizations of the optical light path can be used to encode more information — in essence, to further pack even more bits per transmitted symbol. Such a technique, known as polarization division multiplexing (PDM) or dual polarization (DP), enables doubling the number of transported bits while keeping the same symbol rate compared to a standard single polarization signal.

By combining the information into a phase-domain and polarization-domain modulation format, effective and reliable high speed transmission can be achieved with a high degree of quality and performance. This solution, however, requires the introduction of a different type of receiver with respect to conventional optical transmission: a compact, cost-effective and adaptable electro-optical design that uses coherent detection techniques coupled with advanced, ultra-fast digital signal processing.

2. Detection techniques

On the receiver side, three main methods can be used to detect the information carried by an optical signal:

- *Direct detection* — Uses a photodiode that generates an electrical current proportional to the intensity of the detected optical signal. This simplest method is used to detect an amplitude-modulated ASK signal but is restricted by performance to lower-rate signals, up to 10 Gb/s.
- *Differential (balanced) detection* — Uses an optical interferometer to convert phase changes into intensity changes that can be detected by a photodiode: a mandatory step in detecting phase-modulated formats while keeping the design of the receiver relatively simple. The interferometer compares each symbol with the previous one, providing at its two outputs an electrical current depending on the phase change from one symbol duration to the next. Two photodiodes are connected to the outputs of the interferometer, allowing for balanced detection that provides a 3-dB improvement in noise sensitivity compared to direct detection.
- *Coherent detection* — The receiver mixes the optical signal with a local oscillator — a continuous wave (CW) laser — running at approximately the same optical frequency. A rich set of information contained in the phase, amplitude and polarization of the optical signal is recovered from the interferences resulting from the mixing process onto a series of photodiodes. Coherent detection provides an extra 2-dB noise sensitivity improvement compared to differential detection.

2.1 Differential detection

Differential balanced detection can be efficiently combined with advanced phase-modulation formats. However, this solution remains highly sensitive to linear-transmission fiber impairments — for example PMD and CD — and is therefore unable to perform well in all cases of existing networks, for example, in the case of high-PMD fiber or residual CD. In addition, such conventional detection technology does not provide the most efficient solution for 100 Gb/s wavelength transport, with performance that is certainly not in line with the 10 Gb/s-like reach performance generally expected from network service providers.

2.2 Coherent detection

Coherent detection is the same method as applied in microwave transmission receivers. When applied to wavelength transmission, a spectrum of phase modulated signals in a wavelength is received on an optical mixer. A local oscillator (DC constant power laser) tuned at a ITU-T 50GHz grid is also sent on the mixer and, through beating, only the optical signal at the same frequency is amplified (constructive beating) while all the other frequencies are attenuated because they are not coherent with the local oscillator. Successfully applying this technique requires heavy digital signal processing capabilities, which can only be accomplished in ultra-high-speed silicon.

An effective coherent solution is provided by the combination of coherent detection, ultra-high-speed DSP in the coherent receiver, and a phase-modulated format such as BPSK or QPSK. Although the coherent receiver architecture is more complex than in conventional solutions, the coherent solution offers two key advantages:

- Retrieval of the full information transported by the optical field, giving access to all signal information, such as polarization, amplitude and phase. This introduces tremendous opportunities for DSP to compensate for linear distortions such as CD and PMD, which are induced by transmission within the optical fiber.
- Use of both orthogonal polarizations of the optical signal for encoding multiple information. Polarization division multiplexing (PDM) doubles the transported capacity and increases the spectral efficiency while maintaining compatibility with 50 GHz channel spacing in optical filters, as supported in the Reconfigurable Optical Add-Drop Multiplexer (ROADM) installed base.

3. Alcatel-Lucent next-generation coherent electro-optics technology for best-in-class 40 Gb/s and 100 Gb/s transmission

Among the various phase-domain and polarization-domain modulation formats that can be combined and associated with coherent detection, Alcatel-Lucent has selected and invested in the following two options, which solve the challenges of economically viable high-speed electro-optical transmission by achieving best-in-class performance and efficiency:

- *PDM-BPSK with coherent detection for best-in-class 40 Gb/s transmission:* The signal is a combination of PDM and one single carrier BPSK-modulated carrying one bit per symbol and travelling at 20 Gbaud symbol rate (excluding the relevant bandwidth amount for overhead forward error coding [FEC]). It offers best performance in ultra-long distances due to its excellent resilience to non-linear effects and transmission compatibility with existing 10 Gb/s non-return-to-zero (NRZ) ASK signals.
- *PDM-QPSK with coherent detection for best in class 100 Gb/s transmission.* The signal is a combination of PDM and one single carrier QPSK-modulated carrying two bits per symbol and travelling at 25 Gbaud symbol rate (excluding the relevant bandwidth amount for overhead and FEC). It is optimized to transport larger capacity thanks to its best reach, best resilience to fiber impairments and excellent compatibility with existing 10 Gb/s and 40 Gb/s channels base.

By leveraging Bell Labs innovation and building on a unique, ultra-fast baud-rate DSP engine with advanced algorithms in a highly integrated and power efficient design, Alcatel-Lucent implements its next-generation 40G and 100G electro-optics technology with coherent detection on its leading photonic platforms.

3.1 Overcoming fiber impairments for best performance

In today's WDM networks, chromatic dispersion is compensated by fixed or tunable optical dispersion compensation modules (DCMs or TDCMs). DCM bulks are usually distributed along the optical line at each amplification site, and they impact the transmission reach by adding non-linear effects and optical noise due to the need for supplementary amplification to compensate for the losses they introduce. Electro-optics with coherent technology enables electronic-based dispersion compensation at the receiver end, removes the need for dispersion-management devices from the line and improves the total transmission reach.

Conventional 40 Gb/s technology also requires optical TDCM on the receiver side to finely tune the residual dispersion because in-line dispersion management techniques can only provide a limited amount of compensation, which is usually insufficient to cover all network applications. Moreover, TDCM tuning time is typically in the order of minutes, and this severely impacts fast wavelength re-configuration when photonic network restoration is implemented. On the contrary, high-performance electro-optics with coherent technology uses fast electronic compensation by means of advanced DSP algorithms and offers dispersion compensation in a time frame of milliseconds, offering much higher flexibility in network reconfigurations and much faster wavelength restoration capabilities.

In old-fiber infrastructures, PMD is a very critical factor for signal propagation impairments because it introduces signal distortion penalties that prevent high-performance transmission of 40 Gb/s or 100 Gb/s signals. The advanced DSP techniques used in the coherent solution can best compensate the effects of PMD and seamlessly enable 40 Gb/s and 100 Gb/s transmission over any fiber network.

These benefits translate into superior performance of 40G PDM-BPSK and 100G PDM-QPSK with coherent detection, as shown in Figure 1.

Figure 1. Best-in-class, next-generation coherent 100-G transmission

Benchmarking 100G wavelength transport	PDM-QPSK (single carrier coherent)	FDM PDM-QPSK (coherent)	OPFDM RZ-DQPSK (non-coherent)	PDM-DQPSK (non-coherent)
	50 GHz slot	50 GHz slot	100 GHz slot	50 GHz slot
Transmission reach	Best	Why?	Single carrier coherent fast baud rate minimizes non-linear effects	
Polarization mode and chromatic dispersion tolerance	Best	Why?	Coherent technology with advanced DSP compensates linear effects	
Compatibility with 10G and 40G neighbors	Best	Why?	Single carrier coherent fast baud rate minimizes cross-channel non-linear effects	
Filtering (ROADM cascading)	Best	Why?	Single carrier into one 50 GHz slot maximizes the number of traversing OADMs before OEO	
Power consumption and footprint	Best	Why?	Single carrier coherent highly integrated design maximizes the integration of functions in CMOS	
Cost and complexity	Best	Why?	Single carrier coherent highly integrated design minimizes complexity and cost	

3.2 Existing network upgrades

An important issue when addressing photonic network upgrades is the compatibility with existing channels transmitted at lower rates — for example, conventional 10 Gb/s and 40 Gb/s channels with different modulation formats – along with the ability to adapt to existing old fiber plants.

Next-generation electro-optics with coherent detection technology enables seamless upgrade to higher bit-rate channels of existing networks that were originally designed for 2.5 Gb/s or 10 Gb/s capacity, with the following benefits:

- Automatic, electronic-based compensation for large CD amounts allows for seamless deployments of new 40 Gb/s and 100 Gb/s channels using the existing DCMs.
- Highly tolerant dispersion compensation enables the deployment of 40 Gb/s and 100 Gb/s channels even in old-generation fiber plants that were originally designed without DCMs for 2.5 Gb/s transport.
- Excellent PMD compensation enables the upgrade to 40 Gb/s and 100 Gb/s of old-fiber networks with high PMD values, in which even transmission of 10 Gb/s channels would be a challenge.

It has been demonstrated that a 40 Gb/s QPSK-based signal — transmitted at 10 Gbaud symbol rate — can suffer from non-linear interferences induced by 10 Gb/s neighbor channels, especially when transmission occurs over low-dispersion fiber such as ITU-T G.655. Such cross-phase modulation (XPM) effect occurs because the 10Gbaud amplitude variations of traditional 10 Gb/s ASK-modulated channels generate 10Gbaud phase noise on the 40 Gb/s signal — being at a virtually equivalent rate — and make it more difficult to detect the four phase states at the 40 Gb/s receiver. Such interference can dramatically reduce the maximum reach of 40 Gb/s channels when they are spectrally adjacent to 10 Gb/s channels.

A possible mitigation is to introduce guard bands — that is, multiple empty spectral slots — between conventional 40 Gb/s channels and 10 Gb/s channels; however, this tends to severely reduce the maximum fiber capacity and limit the freedom in channel allocation in case of network reconfigurations.

The selection of the optimal modulation format with the highest tolerance to non-linear effects, and combining it with coherent detection, enables offering the best-in-class option for maximum transmission reach and highest compatibility with existing 10 Gb/s neighbor channels.

Next-generation electro-optics implementing PDM-BPSK and PDM-QPSK with coherent detection offers the best-in-class solution for 40 Gb/s and 100 Gb/s transmission, respectively. Their single carrier, high symbol rates at 20 Gbaud and 25 Gbaud, respectively, are very robust to non-linear effects and are highly tolerant to 10 Gb/s adjacent channels.

3.3 Greenfield network deployments

In new network deployments, 40G and 100G next-generation electro-optics with coherent technology offer high spectral efficiency compatible with 50-GHz spacing, best-in-class reach, performance and dispersion-compensation plus high PMD tolerance. In greenfield optical network scenarios without 10 Gb/s wavelengths, all new traffic can be deployed using 40G and 100G next-generation coherent technology, eliminating the need for optical DCMs with the following benefits:

- Eliminates the cost of DCMs
- Reduces the accuracy needed in quantifying dispersion and fiber span length, eliminating significant operational costs associated with optical characterization of the fiber infrastructure
- Maximizes transmission reach by slashing transmission penalties associated with the non-linear effects and losses that occur when using DCMs

4. Leads and executes innovation

Leveraging Bell Labs innovation, Alcatel-Lucent has long invested in research and experiments in 100 Gb/s transmission and next-generation coherent technology, providing prominent contributions to the scientific community starting in 2005.

In November 2007, Alcatel-Lucent performed the industry's first field trial of 100 Gb/s optical transmission on a live, in-service 504-km network route between Tampa and Miami, Florida in the United States over the Verizon® network. This led to a 100 Gb/s plug-and-play demonstration on an already-installed Alcatel-Lucent dense WDM (DWDM) system. The demonstration was based on the RZ-DQPSK modulation scheme, and the trial virtually opened the road to 100 Gb/s transmission in a real-world network.

More recently, in November 2009, Alcatel-Lucent performed a field trial in Telefónica's network in Spain, by transmitting a 112 Gb/s channel with commercial margins together with 40 Gb/s and 10 Gb/s channels on a 1088-km link between Madrid and Merida by way of Seville. This trial, which used the state-of-the-art PDM-QPSK modulation format and a coherent receiver, demonstrated for the first time the smooth upgrade capability to 100 Gb/s of a commercial link that was heavily loaded with 10 Gb/s channels with paying traffic.

Alcatel-Lucent delivers best-in-class 100G PDM-QPSK and 40G PDM-BSPK next-generation coherent technology in its photonic platforms, leveraging highly integrated silicon, ultra-fast monolithic DSP, unique algorithms and high gain forward error correction (FEC) techniques.

A key component of the Zero Touch Photonics approach for transforming WDM into managed photonic networking and an essential capacity enabler for the Alcatel-Lucent High Leverage Network™ architecture, the 100G and 40G next-generation coherent technology lowers overall TCO with effective scaling, helping operators reduce network design complexity and operations while offering an unmatched level of scalable optical capacity at best-in-class performance.

Table 1. Advantages of next-generation coherent detection technology

FOR EXISTING NETWORKS	FOR NEW NETWORKS
Reuse of existing fiber (even old fiber with a high PMD coefficient) and deployed DCMs	High dispersion and PMD tolerance, allowing for simpler operational characterization of fiber infrastructure
Reuse of existing equipment even 100 Gb/s because high spectral efficiency allows transmission at 50 GHz spacing	No need for DCMs
High tolerance to neighboring channels of regardless of their modulation and bit rate	Higher tolerance to non-linear effects, optical noise and filtering, allowing for longer non-regenerated reach

5. References

5.1 Hero experiments and standardization leadership

Leveraging Bell Labs innovation, Alcatel Lucent has been at the forefront of 100G research, reporting the first laboratory transmission record at ECOC 2005:

- P. Winzer et al. 107-Gbps optical ETDM transmitter for 100G Ethernet transport. Post-deadline paper Th4.1.1. Glasgow, Scotland, September 2005.

Since 2005, Bell Labs teams have continuously reported transmission records at both 40Gbps and 100Gbps, demonstrating the leadership of Alcatel-Lucent in coherent technology:

- G. Charlet et al. Transmission of 81 channels at 40Gbit/s over a Transpacific-Distance Erbium-only Link, using PDM-BPSK Modulation, Coherent Detection, and a new large effective area fibre. ECOC 2008, Th3.E.3, September 2008.
- G. Charlet et al. 72x100Gbps transmission over transoceanic distance, using large effective area fiber, hybrid Raman-Erbium amplification and coherent detection. OFC 2009 post-deadline paper PDPB6. San Diego, California, United States, March 22 to 26, 2009.
- M. Salsi et al. 155x100Gbit/s coherent PDM-QPSK transmission over 7,200km. ECOC 2009, September 2009.

Since the beginning, Alcatel-Lucent has been a leader in the standardization of 100 GigE and 40 GigE in the Institute of Electrical and Electronics Engineers (IEEE). Alcatel-Lucent is also a major player within the ITU-T and Optical Interworking Forum (OIF) for the consistent transport of 100 GigE and 40 GigE within Optical Transport Unit 3 (OTU3)/OTU4.

5.2 Standards

- ITU-T G.652. Characteristics of a single-mode optical fibre cable.
- ITU-T G.655. Characteristics of a non-zero dispersion shifted single-mode optical fibre cable.

5.3 Press releases

Verizon Successfully Completes Industry's First Field Trial of 100 Gbps Optical Network Transmission, November 2007:

- http://all.alcatel-lucent.com/wps/portal/!ut/p/kcxml/04_Sj9SPykssy0xPLMnMz0vM0Y_QjzKLt4w3czLXL8h2VAQA9ypdMQ!!?LMSG_CABINET=Docs_and_Resource_Ctr&LMSG_CON-TENT_FILE=News_Releases_2007/News_Article_000653.xml

Alcatel-Lucent further advances 100G transmission by integrating advanced developments in next-generation coherent detection on its optical platforms, November 2009:

- http://all.alcatel-lucent.com/wps/portal/!ut/p/kcxml/04_Sj9SPykssy0xPLMnMz0vMOY_QjzKLt4w3czLXL8h2VAQA9ypdMQ!!?LMSG_CABINET=Docs_and_Resource_Ctr&LMSG_CON-TENT_FILE=News_Releases_2009/News_Article_001901.xml

6. Contacts

For more information about Alcatel-Lucent's next-generation coherent technology, High Leverage Network™ architecture and Zero Touch Photonics approach, please visit www.alcatel-lucent.com or contact your Customer Team representative.

7. Acronyms

Baud	symbols per second
BPSK	binary phase-shift keying
CD	chromatic dispersion
CW	continuous wave
DCM	dispersion compensating module
DP	dual polarization
DPSK	differential phase-shift keying
DQPSK	differential QPSK
DSP	digital signal processing
DWDM	dense WDM
FDM	frequency division multiplexing
FEC	forward error correction
IEEE	Institute of Electrical and Electronics Engineers
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
NRZ	non-return to zero
OIF	Optical Interworking Forum
OPFDM	orthogonally polarized FDM
OTU	Optical Transport Unit
P-DPSK	partial differential phase shift keying
PDM	polarization division multiplexing
PMD	polarization mode dispersion
PMDC	PMD compensator
QPSK	quaternary phase-shift keying
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RZ-DQPSK	return-to-zero DQPSK
TDCM	tunable DCM
TOADM	Tunable Optical Add-Drop Multiplexer
WDM	wavelength division multiplexing

www.alcatel-lucent.com Alcatel, Lucent, Alcatel-Lucent and the Alcatel-Lucent logo are trademarks of Alcatel-Lucent. All other trademarks are the property of their respective owners. The information presented is subject to change without notice. Alcatel-Lucent assumes no responsibility for inaccuracies contained herein. Copyright © 2010 Alcatel-Lucent. All rights reserved.
CPG4688100618 (06)

