White paper

Space Division Multiplexing: A new milestone in the evolution of fiber optic communication

Nokia Siemens Networks

Executive summary

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A fundamentally new approach will be needed to meet the continuously increasing capacity of the world's long haul optical communications networks and to prevent a "capacity crunch" as hyper-growth in demand for data continues. That increase will only be possible with a step-change in state-of-the-art optical technology.

What are the limitations associated with using current fiber technology and which technologies are likely to unlock the added capacity that operators need? This paper reviews the latest research in mode multiplexing over advanced multi-mode fibers, looking beyond what's possible today towards innovative hollow-core fibers.

Rapid progress is being made in the area of Space Division Multiplexing (SDM), with Nokia Siemens Networks' optical networks group achieving record-breaking capacity breakthroughs in recent months. There is every reason to be confident that further research will overcome the remaining technical challenges and successfully avoid the capacity crunch altogether.

Rising traffic demands a step-change in network capacity

Optical networks form the backbone of modern communications networks, transporting data traffic anywhere from a few kilometres right up to distances on a transcontinental scale. These fiber "highways" have already evolved significantly since their inception. When fiber technology started to replace copper wire in the 1980s, first generation systems operated at bit rates of 45 Mb/s and needed support from repeaters every 10 km. Today's longhaul networks offer 100 Gb/s per wavelength, thanks to the arrival of coherent technology.

A brief history of optical communication

- The original optical format used on-off-keying (OOK), with bits indicated by "light on" and "light off" states.
- The introduction of differential binary phase shift keying (DPSK) increased the receiver sensitivity and as such allowed for higher data rates, whereas differential quadrature phase shift keying (DQPSK) doubled the spectral efficiency.
- Capacity was then increased by increasing the bandwidth, but higher bandwidth is more vulnerable to distortion, so there are limits on how far this approach can go.
- Spectral efficiency was doubled yet again by transmitting and receiving information in two orthogonal polarizations.
- The arrival of coherent technology solved many underlying issues. Nokia Siemens Networks released its coherent transponder technology for 40 Gb/s in 2009. This was followed by 100 Gb/s in 2011.

Coherent technology blends optics and electronics, transforming the optical signal to the electrical domain by mixing it with a reference of the carrier frequency. This enables data to pass between the two domains complete with amplitude, polarization and phase information, which was not previously possible. Today's coherent systems typically use a so-called 50 GHz grid. They have a reach in excess of 2,500 km depending on fiber type and system configuration.

Coherent detection with digital signal processing (DSP) improves receiver sensitivity, spectral efficiency and impairment compensation to increase the robustness and performance of the system, as shown in Table 1. Finally, the transmitter and receiver structures remain the same regardless of the modulation format. This makes it possible to deploy flexible rate transponders that use varying modulation formats depending on the given reach in the system.

Feature of coherent technology	
Increased sensitivity	No differential demodulation penalty
Spectral efficiency	Factor of 2 for two polarizations of light and two quadratures (I and Q)
Linear impairment compensation	CD, DGD, PDL, WSS filtering
Advanced DSP	Soft-decision FEC, spectral shaping, nonlinear impairment compensation, component impairment mitigation
Future proof	Able to demodulate all formats: BPSK, QPSK, 8QAM, 16QAM

Table 1: Coherent technology as an enabler.

100 Gb/s technology will be at the core of long haul networks for years to come, yet even these data rates will not be enough to cope with future demand.

The boom in traffic associated with the rise in smart devices, video-based applications and developments such as machine-to-machine communication shows no signs of slowing. Network operators are already looking ahead to find ways to deliver future applications, which will require data rates approaching 400 Gb/s and 1 Tb/s. This in turn demands some fresh thinking, because it will take a combination of approaches to overcome the technical challenges of providing these data rates.

In practical terms, today's combination of standard single-mode fibers and erbium doped fiber amplifiers (EDFA) is fundamentally incapable of delivering data rates of 400 Gb/s or 1 Tb/s over distances of more than 1,000 km including end of life system margins.

The limits of single-mode fibers

There are several approaches that may boost the capacity of standard, single-mode fibers, but they all have their limitations.

The first is to look at changing the modulation format to achieve higher spectral efficiency. All else being equal, the best this is likely to manage is a doubling of capacity, because the signal will be affected by noise as it passes through multiple amplifiers and nonlinear effects from the transmission process.

Going any further would in theory require the use of "super-channels" that include multiple sub-bands beyond the 50 GHz grid. Basic fiber characteristics such as loss and refractive index mean that this approach depends on the availability of advanced fiber types with lower non-linearity and loss that would not need such frequent amplification, as well as swapping EDFA technology for less noisy Raman (optical) amplification. Even with these advances, the reach will remain limited, so that 400 Gb/s and 1 Tb/s running on legacy systems will be unable to bridge distances greater than 2,000 km in long haul links with high spectral efficiency.

These issues all lead to a theoretical maximum achievable spectral efficiency for 2000 km of single-mode fiber of less than 7 b/s/Hz. With traffic volumes increasing by around 40% each year, this means that optical networks face a capacity crunch unless a step-change in technology can be achieved.

Is a capacity crunch inevitable with today's technology?

- On a standard single-mode fiber with conventional optical amplifiers, higher order modulation formats cannot reach 2,000 km because of the required high optical signal-to-noise ratio.
- New, ultra-low-loss fibers with a high effective area and Raman amplification will be needed to overcome the 2,000 km limit with data rates of 400 Gb/s or more.
- Employing FlexiGrid, the improvements in spectral efficiency over standard single-mode fiber will only achieve a 20% boost in capacity, leading to a significant shortfall.

Spatial multiplexing: delivering room for improvement

There are several ways to increase optical transmission system capacity over a fixed bandwidth, and most of them are already being used, including modulation using different amplitude levels, two orthogonal subcarriers (cosine and sine modulation) and polarization.

Frequency is also used in wavelength division multiplexing (WDM).

In fact, the only remaining unused dimension is space, and there are two basic strategies for achieving spatial separation within a fiber - multi-core and multi-mode operation.

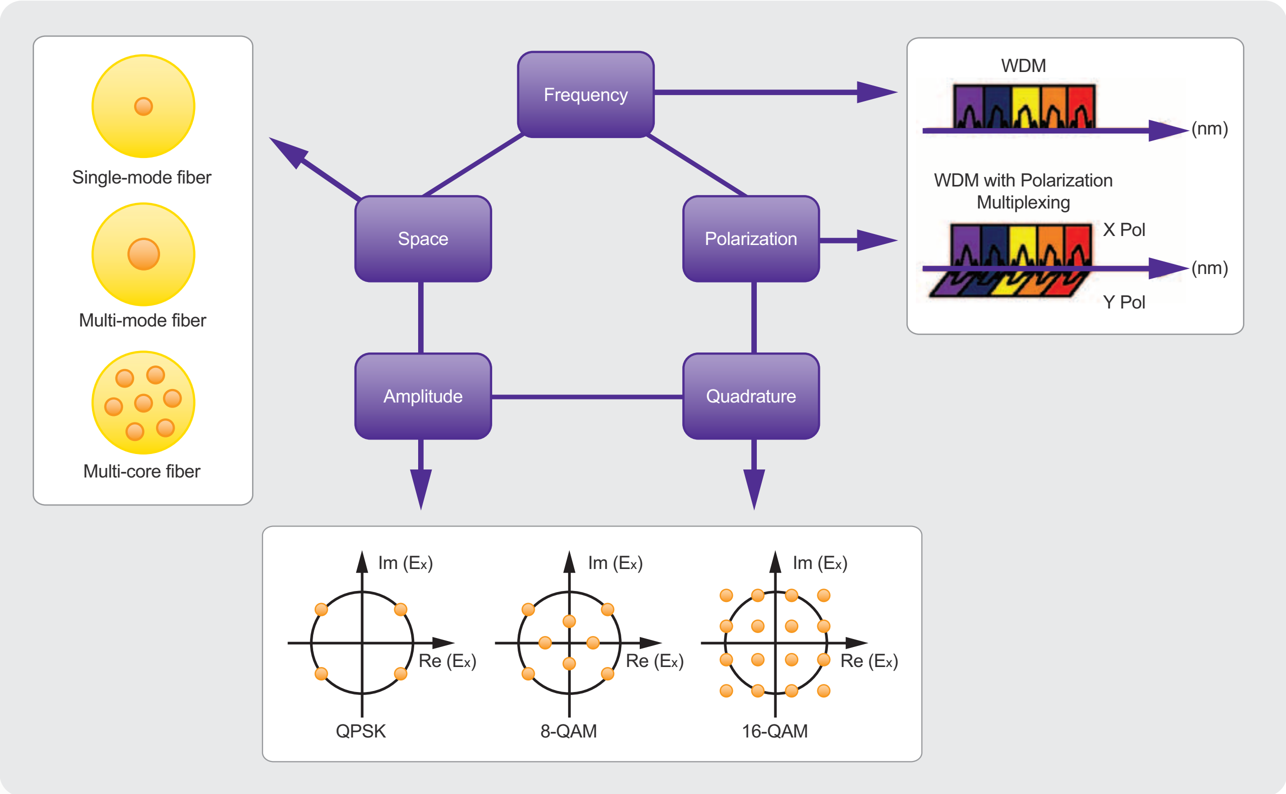

Figure 2: Ways to modulate and multiplex channels to increase system capacity in optical transmission.

Multi-core and multi-mode fibers

Multi-core fibers have several cores embedded in the fiber cladding. However, the cores are not fully separated so there will be crosstalk between them, which ultimately limits the transmission performance or requires complex DSP to untangle the signals. In addition, a single-mode glass fiber core will not be able to achieve a lower loss or higher non-linear tolerance than standard single-mode fibers, since these are basic properties of the material. That limits any increase in capacity in step with the number of cores in the fiber.

On the other hand, multi-mode fibers allow the propagation of several independent modes within a single core.

The number of modes that a fiber supports is determined by the core size and the refractive index of the fiber. Increasing the size of the core allows for more modes to be supported inside the fiber. Typical commercial multi-mode fibers support several tens to hundreds of modes and are used for short distances. However, Nokia Siemens Networks has carried out experiments with “few mode fibers”, which support a handful of modes that are all excited independently.

Multi-mode fibers offer more efficient amplification than multi-core fibers, leading to potentially lower amplification costs, revealing a path towards a large ROADM integration based on wavelength selective switching of multi-mode signals, and with a lower nonlinearity than single-mode fibers due to the larger effective area.

Solid-core record breaker

In 2012, Nokia Siemens Networks demonstrated a record capacity of 57.6 Tb/s transmitted over multi-mode fibers. This is six times the capacity of current 100 Gb/s systems and more than doubles the previous record over multi-mode fiber.

The demonstration featured 200 Gb/s DP-16QAM per mode and wavelength transmitted over three spatial modes and 96 channels in the extended C-band. The transmission distance was 119 km with inline multi-mode amplification.

Hollow-core fibers

As fundamental physical constraints, loss and non-linear tolerance hold the key to increasing spectral efficiency, especially if they can be improved alongside multiple modes and perhaps even a wider spectrum of wavelengths for transmission.

Hollow-core fibers have the potential to offer a solution. In these fibers, the signal propagates in air, not glass. As well as offering a possible answer to capacity issues, they also offer lower latency, which is increasingly important in many applications.

Whereas glass fibers guide the light using total internal reflection, hollow-core fibers confine the light to the core using a cladding structure that acts as a grating. Offering a potential loss of smaller than 0.1dB/km and a nonlinear coefficient 1,000 times lower than a conventional single-mode fiber, hollow-core fibers promise huge increases in spectral efficiency.

However, hollow-core fiber deployments will not be here for some time. For example, state-of-the-art hollow core fibers still have a loss several times higher than standard single-mode fibers. One of the main challenges lies in bringing this loss down.

Given these constraints, Nokia Siemens Networks is driving the development of hollow core fibers for potential low latency applications. Latency is a critical factor in an increasing number of applications, ranging from data center applications to economically critical financial transactions. Hollow-core fiber offers a 30% lower inherent latency than common silica glass and can reduce transmission times by several milliseconds, which represents a true game changer for latency-critical applications.With this in mind, Nokia Siemens Networks believes there is a promising target application of single-mode transmission over hollow core fiber, introducing hollow-core fibers first in the common 1.55 m window using all available technology.

Hollow core record breaker

Nokia Siemens Networks demonstrated record-breaking single mode capacity over hollow-core fiber in the first ever demonstration of coherent technology over this fiber type. The experiment achieved a capacity of 24 Tb/s.

The researchers used single-mode transmission of 96 wavelength channels carrying dual polarization 32QAM modulation.

The pros and cons of different fiber types

Multi-core	Multi-mode solid core	Multi-mode hollow core
+ Highest data rates achieved so far	+ Potentially lowest system cost	+ Lowest latency (<-30%)
+ Enabling higher density of integration for transponders and amplifiers	+ Enabling higher density of integration for transponders and amplifiers, ROADMs	+ Enabling higher density of integration for transponders and amplifiers
+ Can be combined with multi-mode	+ Higher reach due to lower nonlinearity	+ Lowest potential loss (<0.1dB/km) @ 2 μm
- No advantage in reach (same loss, nonlinearity)	+ More efficient pumping than multi-core	+ 4 x bandwidth @ 2 μm
- Same bandwidth as SSMF	- Same bandwidth as SSMF	+ Very low nonlinearity
- Fiber crosstalk needs to be further reduced	- Equalization of mode cross talk required in DSP	- Mode dependent loss is intrinsic and leads to performance degradation
- No ROADM integration	- Mode dependent loss can lead to performance degradation	- Very high differential group delay requires huge DSP complexity for mode multiplexing
	- Scalability to higher number of modes is tough	- No long reaches demonstrated so far (record reach <1 km)
		- Losses so far are well above SSMF

Table 2: The pros and cons of different fiber types.

Conclusion

Nokia Siemens Networks believes that the new technologies described hold great potential, despite the challenges that remain. These challenges include a scaling up of number of modes in few mode fibers, manufacturability of hollow core fiber and the development of a multi-mode based component ecosystem. Furthermore, Nokia Siemens Networks is developing the proper tools to handle the impairments of these new fiber types at the system level and to enable new high capacity and low latency transmission. Significant progress in these new optical components has already been made and the main challenge will therefore be to identify if and how multi-mode transmission will be able to achieve long-haul transmission distances greater than 2,000 km.

There are several possible avenues for taking this work forward, including the multiplexing and de multiplexing of modes and/or mode groups (a group of modes containing the same properties), fiber characteristics that allow for low-complexity DSP and robust transmission, multi-mode amplifiers and DSP that is fast, stable and able to unravel the modes and allow for higher data-rates.

Nokia Siemens Networks is already a pioneer in the field of optical transmission systems and intends to maintain that position by increasing the capacity per fiber 100-fold. Recent research has already made great strides, with Nokia Siemens Networks breaking records for transmission over solid-core multi-mode fibers and being the first to transmit coherently-detected modulation formats over hollow core fiber.

Even as they become available, the significant investment needed to deploy new fiber technologies means that the substitution of today's optical networks will be a gradual process, with high-priority areas of the network making the change first, followed ultimately by the rest.

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