

# SPACE DIVISION MULTIPLEXING A New Milestone in the Evolution of Fiber Optic Communication

With the proliferation of smart devices, video-based applications and developments such as machine-to-machine communication, the demand for data capacity is increasing at a staggering rate that shows no signs of slowing. Today's 100 Gbps technology will be at the core of long-haul networks for years to come but will not be enough to handle future demand. Network operators are now seeking ways to deliver future applications that require rates nearing 400 Gbps and 1 Tbps, but are faced with the constraints inherent in today's optical technology. For long-haul optical communications networks, this means an impending "capacity crunch." In order to fully address the discrepancy between technology-readiness and anticipated demand, a paramount change to today's technology is needed.

This paper reviews the constraints of current fiber technology and examines the technologies likely to break through capacity barriers. The discussion looks at the latest research in mode multiplexing over advanced multi-mode fiber, as well as at the hollow-core fiber technology of tomorrow. Rapid progress is being made in the area of Space Division Multiplexing (SDM), led in part by Coriant's research and record-breaking capacity breakthroughs. These and other advances suggest that the industry's remaining technical barriers can be overcome and the impending "capacity crunch," mitigated or avoided altogether.

# **A BRIEF HISTORY**

Today's optical networks form the backbone of modern communications networks, transporting data traffic across distances of just a few kilometers to clear across continents. These fiber "highways" have evolved significantly since their inception in the 1980s when fiber technology started to replace copper wire. The first generation systems operated at bit rates of 45 Mbps and needed support from repeaters every 10 km.

#### **OPTICAL COMMUNICATION HISTORICAL HIGHLIGHTS**

- The original optical format used spectrally inefficient on-off-keying (OOK), with bits indicated by "light on" and "light off" states
- The introduction of differential binary phase shift keying (DPSK) doubled the spectral efficiency and differential quadrature phase shift keying (DQPSK) doubled it again
- Capacity was then increased by upping bandwidth. Yet higher bandwidth is more vulnerable to distortion, which limited this approach
- Spectral efficiency was doubled yet again by transmitting and receiving information in two orthogonal polarizations
- The arrival of coherent technology solved many underlying issues. Coriant released its coherent transponder technology for 40 Gbps in 2009. This was followed by 100 Gbps in 2011

# **COHERENT TECHNOLOGY**

Thanks to the introduction of coherent technology, today's long-haul networks provide 100 Gbps per wavelength. 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 and phase information, which was previously not possible.

Today's coherent systems typically use a 50 GHz grid, which have a reach in excess of 2,500 km depending on fiber type and system configuration.

Coherent technology improves receiver sensitivity, spectral efficiency and impairment compensation. Teaming coherent technology with digital signal processing (DSP) enables even more advanced features that 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 system's given reach.

COHERENT TECHNOLOGY FEATURES	CAPABILITIES
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, non- linear impairment compensation, component impairment mitigation
Future-proof	Able to demodulate all formats: BPSK, QPSK, 8QAM, 16QAM

#### TABLE 1

Coherent technology as an enabler

## THE LIMITS OF SINGLE-MODE FIBER

Today's technology, a combination of standard single-mode fiber and erbium doped fiber amplifiers (EDFA), is fundamentally incapable of delivering data rates of 400 Gbps or 1 Tbps over distances greater than 1,000 km. Though all come with constraints, there are several methods for boosting the capacity of standard single-mode fiber.

The first is to change the modulation format for higher spectral efficiency, with the doubling of capacity as the best likely outcome. These limitations result from the impact noise and non-linear effects have on the signal as it passes through multiple amplifiers during the transmission process.

In theory, further increasing capacity would 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 make this method dependent on the availability of advanced fiber types with lower non-linearity, loss requiring infrequent amplification, and the ability to swap EDFA technology for less noisy Raman (optical) amplification. Even under these ideal circumstances, reach remains limited. In long-haul links running on legacy systems, rates of 400 Gbps and 1 Tbps are unable to bridge distances greater than 2,000 km.

These constraints result in a theoretical maximum achievable spectral efficiency of less than 7 b/s/Hz for 2,000 km of single-mode fiber. With traffic volumes increasing by approximately 40% each year, a "capacity crunch" is likely unless these technology barriers can be mitigated.

### THE "CAPACITY CRUNCH" AND TODAY'S TECHNOLOGY

Due to the required high signal/noise ratio on a standard single-mode fiber with conventional optical amplifiers, higher order modulation formats cannot reach 2,000 km.

For data rates of 400 Gbps or more, new ultra-low-loss fiber with a high effective area and Raman amplification is needed to exceed today's 2,000 km limit.

Employing FlexiGrid, improvements in spectral efficiency over standard single-mode fiber can increase capacity by only 20%, which falls significantly short of anticipated demand requirements.

## SPATIAL MULTIPLEXING

There are several possible methods for increasing transmission capacity over fixed bandwidth, most of which are already in use. These include modulation employing 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. There are two basic strategies for achieving spatial separation within a fiber – multi-core and multi-mode operation.



#### FIGURE 1

Methods for modulating and multiplexing channels in order to increase optical transmission capacity

### MULTI-CORE AND MULTI-MODE FIBER

Multi-core fiber has several cores embedded in the fiber cladding. The cores, however, are not fully separated. This causes crosstalk between them, which ultimately limits transmission performance or requires complex DSP to untangle the signals.

In addition, a single-mode glass fiber cannot achieve a lower loss or higher non-linear tolerance than standard single-mode fiber, as these are basic properties of the material. These characteristics limit increases in capacity in accordance with the number of cores in the fiber.

However, multi-mode fiber allows 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 within the fiber.

### CORIANT: SOLID-CORE RECORD BREAKER

In 2012, Coriant demonstrated a record capacity of 57.6 Tbps transmitted over multi-mode fiber. This is six times the capacity of current 100 Gbps systems and more than double the previous record for transmission rates over multi-mode fiber.

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

In 2013 Coriant demonstrated a reach of more than 1,000 km using QPSK on a link employing multi-mode optical amplifiers.

Typical commercial multi-mode fiber supports several tens to hundreds of modes and is used for short distances. Coriant has, however, conducted experiments with multi-mode fibers. These support a handful of modes that are all activated independently.

Multi-mode fiber offers more efficient amplification than multi-core fiber, resulting in potentially lower amplification costs. This in turn paves the way for a large ROADM integration based on the wavelength selective switching of multi-mode signals.

In 2013 Coriant, jointly with A1 of the Telekom Austria Group, performed the industry's first optical space division multiplexing field trial. The trial included an interoperability demonstration of a live system with multimode equipment and showcased a gradual upgrade scenario for legacy networks.

## **HOLLOW-CORE FIBER**

Loss and non-linear tolerance, two fundamental physical constraints, can increase spectral efficiency when improved alongside multiple modes within a wider spectrum of transmission wavelengths. In hollow-core fiber, the signal propagates in air, not glass. Whereas glass fiber guides light using total internal reflection, hollow-core fiber confines the light to the core using a cladding structure that acts as a grating. Potentially achieving a loss less than 0.1 dB/km and a non-linear coefficient 1,000 times lower than a conventional single-mode fiber, hollow-core fiber promises enormous increases in spectral efficiency.

Despite its potential, however, hollow-core fiber still has a loss several times higher than standard singlemode fiber. Remedying this limitation is currently one of the primary obstacles of deploying hollow-core fiber for the purposes of increasing capacity.

Beyond potentially solving capacity issues, hollow-core fiber offers lower latency, which is increasingly important in data center and financial transaction applications. Hollow-core fiber offers a 30% lower inherent latency than common silica glass and can reduce transmission times by several milliseconds – advantages that prove to be a true game changer for latency-critical applications. Leading research in hollow-core fiber, Coriant sees a promising target application of single-mode transmission, making use of all available technology by first introducing hollow-core fiber in the common 1.55µm window.

### CORIANT: HOLLOW-CORE FIBER RECORD SETTER

In the first-ever demonstration of coherent technology over hollow-core fiber, Coriant demonstrated a record-setting single-mode capacity of 24 Tbps. Researchers used single-mode transmission of 96 wavelength channels carrying dual polarization 32QAM modulation.

In 2013, Coriant demonstrated a capacity of 57.6 Tbps over hollow-core fiber using space division multiplexing.

### CONCLUSION

These new technologies hold significant potential, despite the remaining technical challenges such as upward scaling of modes within a small number of mode fibers, manufacturability of hollow-core fiber, and the development of a multi-mode-based component ecosystem. Coriant is addressing these obstacles with development at the system level and by enabling new high-capacity and low-latency transmission. The challenge now is to achieve multi-mode transmission over long-haul distances surpassing 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.

Coriant has long been a pioneer in the field of optical transmission systems and intends to maintain this position by increasing per fiber capacity by 100-fold. Having made significant strides toward this goal, Coriant has broken records for transmission over solid-core multi-mode fiber and was the first to transmit coherently-detected modulation formats over hollow-core fiber.

Even as new fiber technologies become available, the significant investment needed to deploy them means the upgrade of today's optical networks will be a gradual process. CORIANT HAS LONG BEEN A PIONEER IN THE FIELD OF OPTICAL TRANSMISSION SYSTEMS AND INTENDS TO MAINTAIN THIS POSITION BY INCREASING PER FIBER CAPACITY BY 100-FOLD

Coriant has unique experience with this type of phased transition, acquired while upgrading Telekom Austria Group's A1 network in the world's first field trial of optical space division multiplexing. Moving forward, network technology substitutions will begin with high-priority areas of the network, later followed by the rest of the transitioning network elements.

### **ABOUT CORIANT**

Coriant, founded as an independent company in 2013, is a leading supplier of future-proof optical transport, packet/optical switching and aggregation, and software-defined service control and management solutions to Tier 1 service providers worldwide. Coriant's products and solutions enable fixed line and mobile network operators to reduce operational complexity, increase service velocity, and improve resource utilization as transport networks scale in response to a new generation of high-bandwidth services and applications. The company operates worldwide in more than 48 countries and is headquartered in Munich, Germany. Coriant has R&D centers in Asia, Germany, Portugal and the United States, as well as a state-of-the-art production center in Berlin, Germany.

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