Options for Increasing Subsea Cable System Capacity

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With the development of numerous capacity-hungry applications and cloud-based services, the capacities that must be transported between data centers on different continents are skyrocketing, leading to the crucial need for increasing subsea cable system capacity. This article reviews the diverse options for increasing subsea cable system capacity, with a specific emphasis on the technologies to get close to the upper limit placed on the fiber capacity by the Shannon limit.

Options for Increasing Communication Channel Capacity

A very common strategy throughout communication history for increasing the information rate transported by any communication channel, regardless its technology, has been to use multiple dimensions for parallelizing/multiplexing the data to be transported.

Focusing on optical fiber communication, we have several multiplexing dimensions to play with for increasing subsea cable system capacity:

- **Time –** Increasing the baud rate (number of symbols per second) linearly increases the system capacity.

- **Multi-Level Modulation Format –** Increasing the number of bits per symbol (e.g. QPSK encodes 2 bits per symbol, 8QAM 3 bits per symbol, 16QAM 4 bits per symbol) also linearly increases the system capacity.
- **Wavelength –** Increasing the wavelength (or carrier) count linearly increases the system capacity as well. The number of wavelengths is governed by their spectral spacing (itself dictated by the signal spectrum due to modulation format and pre-propagation spectral shaping) and the submerged repeater bandwidth.
- **Polarization –** In commercial products, two orthogonal States of Optical Polarization (SOPs) are combined and launched into the fiber core. These two SOPs effectively double the information rate transported by a single optical carrier. In the short term the SOP count will stay at 2 and there is no improvement to be expected there.
- **Space –** At the cable level, the space multiplexing dimension is the number of fiber pairs, assuming single-mode, single-core fibers. If multi-core/mode fibers suitable for long-haul transmission are achieved in the future, each core or each spatial mode will be considered as an independent communication channel, and the fiber capacity will be increased linearly with the number of cores/modes (this corresponds to the Spatial Division Multiplexing – SDM – approach).

The capacity achievable inside single-mode fibers is governed by the Shannon limit, which is more and more discussed in the industry as it represents an absolute upper limit on the achievable capacity.

Shannon Limit Drives Maximal Capacity

The Shannon-Hartley theorem developed in the 1940s tells the maximal rate at which information can be transmitted with zero error, using ideal error-correcting code, over a communication channel of a specified bandwidth in the presence of additive white Gaussian noise:

$$C = B \times \log_2\left(1 + \frac{S}{N}\right)$$

where

- C is the channel capacity in bits per second, a theoretical upper bound on the net bit rate (information rate) excluding overhead for error-correction codes;
- B is the bandwidth of the channel in hertz;
- S is the average received signal power over the bandwidth, measured in watts;
- N is the average power of the noise and interference over the bandwidth, measured in watts; and
- S/N is the Signal-to-Noise Ratio (SNR) of the communication signal to the noise and interference at the receiver in the bandwidth of the signal (expressed as a linear power ratio, not as logarithmic decibels).

This upper limit applies to any transmission channel (free space, twisted-pair wire, coaxial cable, etc.). In the case of optical fiber transmission, a communication channel must be understood as, e.g., a state of optical polarization, a fiber core or a fiber mode.

Shannon Limit Also Drives Maximal Spectral Efficiency

Spectral Efficiency (SE) refers to the information rate, expressed in bit/s, that can be transmitted over a given bandwidth in a specific communication system based on a given communication channel. Spectral efficiency is obtained by dividing the channel information rate by the channel bandwidth, and is expressed in bit/s/Hz:

$$SE = \frac{C}{B} = \log_2\left(1 + \frac{S}{N}\right)$$

This is a measure of how efficiently a limited frequency spectrum (like the optical bandwidth offered by subsea cable system repeaters) is utilized.

Shannon Limit Curve

In optical communication industry, the S/N ratio is measured under the form of Optical Signal-to-Noise Ratio (OSNR), which is the ratio between the signal power and the noise power in a 0.1 nm optical bandwidth. OSNR are often expressed using the logarithmic decibel scale:

$$OSNR_{dB} = 10 \times \log_{10}(OSNR)$$

The Shannon limit was established for a quasi-ideal communication channel, where only additive white Gaussian noise was considered (blue line in Figure 1). Propagation inside optical fibers at high-capacity and over long distances requires high optical signal power and the use of periodic optical amplifiers that accumulate nonlinear effects along the optical path. The spectral efficiency is then capped by the so-called nonlinear Shannon limit, which depends on the actual link technology and design. An example of nonlinear Shannon limits is depicted in Figure 1 (based on a 2014 presentation from René-Jean Essiambre, Nokia Bell Labs).

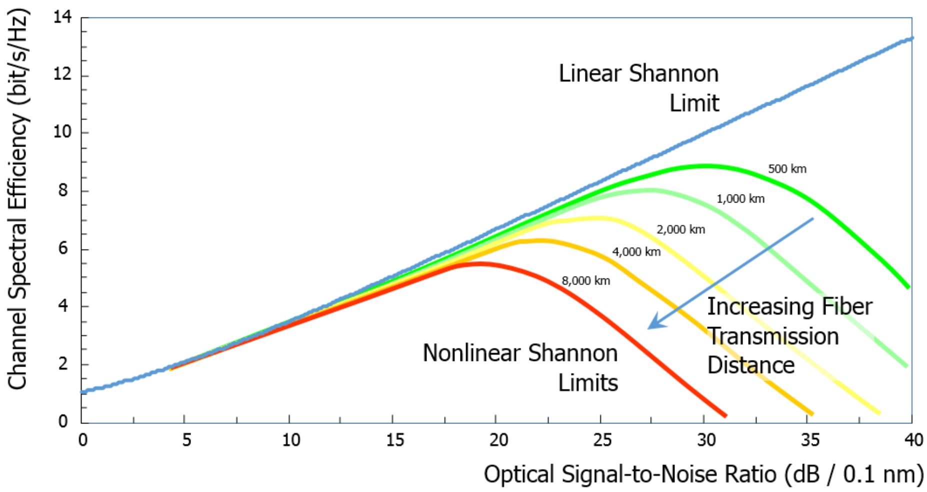

Figure 1: Spectral efficiency as a function of the OSNR for one communication channel

The regions corresponding to spectral efficiencies that can be reached are the areas between the curves and the horizontal axis. For the green curve (500 km), the maximal spectral efficiency is about 8.8 bit/s/Hz while it is about 5.4 bit/s/Hz for the red curve (8,000 km); a factor of 16 in distance does not lead to a drastic change in the spectral efficiency (the achievable capacity is not “even” halved).

Linear Shannon Limit Curve in Coherent Optical Networks

Coherent optical networking equipment uses the optical polarization multiplexing “trick”. The light beam from the laser transmitter is split into two orthogonal states of optical polarization. Each of them is modulated by an independent data stream; then the two states of optical polarization are combined before being launched into the optical fiber. Because the two states of optical polarization are orthogonal, there is no inter-modulation during fiber propagation between the data streams transported by each of them. This technique effectively doubles the amount of data transmitted by a single laser source (emitting a single wavelength) to effectively double the spectral efficiency (as there is no spectral broadening).

Figure 2 shows the linear Shannon limit over the practical OSNR range of interest where most of the coherent optical networks operate, **considering both states of optical polarization**.

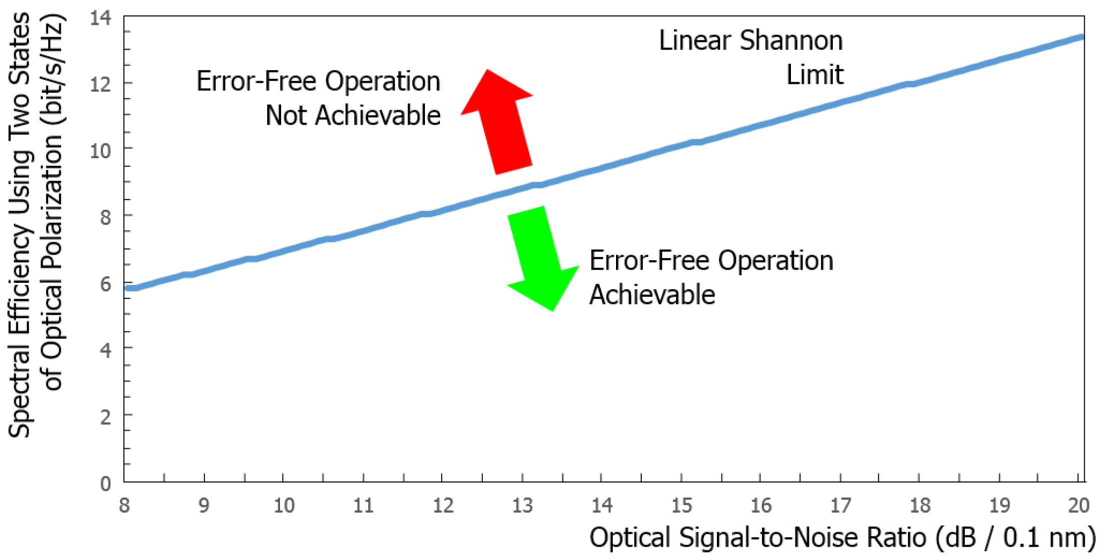

Figure 2: Spectral efficiency as a function of the OSNR for two states of optical polarization

Getting Closer to the Shannon Limit

Three conditions are required to approach the Shannon limit:

- **Nyquist Pulses –** Ideal Nyquist pulse strings lead to zero Inter-Symbol Interference (ISI) at the sampling points if the receiver synchronization is perfectly carried out. In the spectral domain, an ideal Nyquist pulse string results into a quasi-rectangular spectrum with minimal spectral occupancy, allowing many optical carriers to be packed within a given optical spectrum (as imposed by the optical amplifier technology used in the submerged repeaters).

- **Error-Correcting Code –** Coding data for detecting long sequences of bits, detecting/correcting errors and lowering bit error rate. Claude Shannon demonstrated that for any communication channel, there must be an error-correcting code that enables transmissions to approach the Shannon limit. Forward Error Correction (FEC) coding is an active R&D field with the recent introduction of soft-decision and adaptive-rate FEC decoding technologies.
- **Two-Dimension Gaussian Distribution Across Symbol Constellation –** In coherent transmission systems, the information is coded in the amplitude and phase of the optical pulses launched into the optical fiber. Multi-level modulation formats with two-dimension Gaussian distribution of the in-phase and quadrature symbols enable operation close to the Shannon limit. In other words, the symbol patterns effectively launched into the fiber should use often low-amplitude symbols and rarely high-amplitude symbols. A two-dimension Gaussian distribution can be achieved in diverse ways, one of them being constellation shaping, which is a hot R&D topic in the subsea cable system industry.

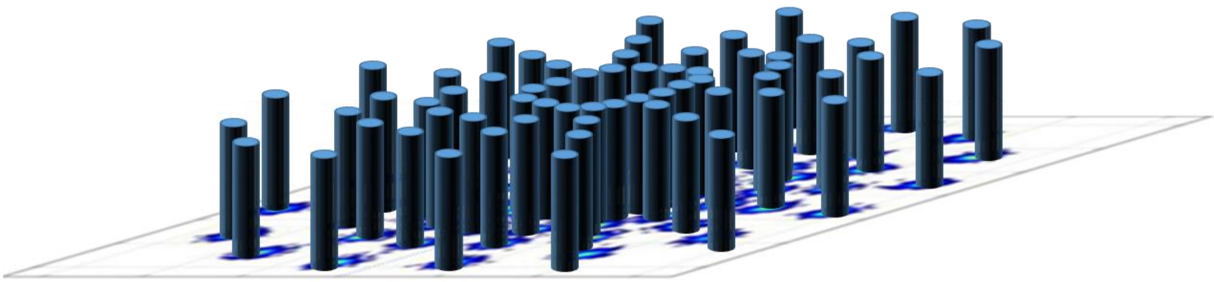

Figure 3: An example of two-dimension gaussian distribution across symbol constellation

Before Constellation Shaping

In most cases, the mapping table, which maps blocks of incoming information bits to the symbols to be transmitted, is such that the Probability Mass Function (PMF) of symbols over the constellation points is a uniform distribution (in other words, the symbols are equiprobable). Probability reminder: a probability mass function is a function that gives the probability that a discrete random variable (like a symbol from a 2^mQAM constellation chart) is exactly equal to some value.

If we take the example of a 16QAM modulation format in Figure 4, the constellation is made of 16 symbols. Four bits are encoded into each symbol. The mapping law is the mechanism that assigns each block of four data bits to a symbol of the constellation. For instance, the 1011 four-bit block is assigned to the (3; 1) symbol in the figure below. In a conventional 16QAM constellation, each of the 16 symbols has an equal chance of being assigned and transmitted. The PMF of each of the four possible in-phase symbol levels is therefore 0.25 (with, of course, the sum of the PMF of the four in-phase symbols being equal to 1). The same applies to 64QAM modulation format, with a PMF of each of the eight possible in-phase symbol levels equal to 0.125 (with 8 x 0.125 = 1), as shown on the right side of Figure 4.

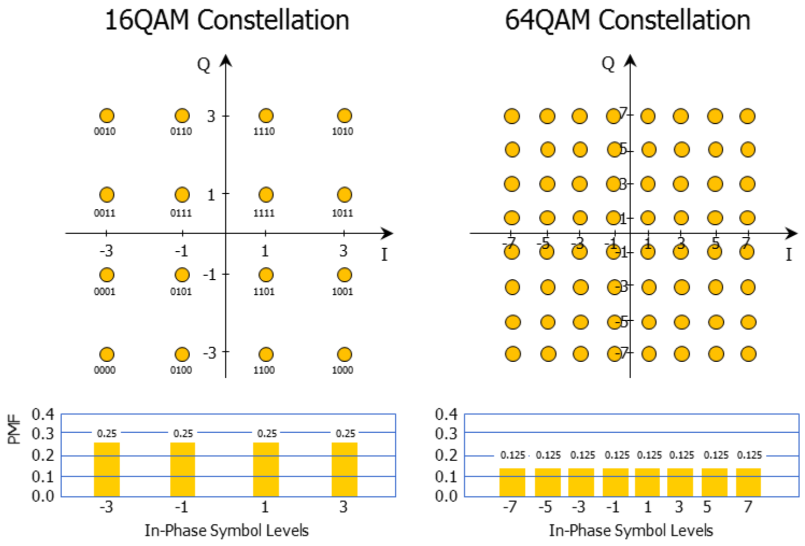

Figure 4: 16QAM and 64QAM signals with no constellation shaping

What Is Constellation Shaping?

It has been shown that the gap between the practically achieved capacity and the theoretically achievable Shannon's capacity is reduced if the modulation format exhibits a two-dimension Gaussian probability mass function for both the in-phase and quadrature components of the constellation symbols. Constellation shaping techniques are an ensemble of various techniques to turn constellations with equidistant, equiprobable symbols (like standard square 16QAM or 64QAM constellations) into more "Gaussian" constellations, with symbols located in the center of the constellation more likely to occur. Probabilistic Shaping (PS) and Geometric Shaping (GS) are the two main options to mimic a "Gaussian-like" shape of the constellation.

Probabilistic Constellation Shaping

Probabilistic shaping imposes a **non-uniform distribution** (i.e. non equiprobable symbols) on a set of **equidistant constellation points**. Probabilistic shaping relies on the use of a code (called distribution matcher) to gradually vary the probability distribution of the constellation points (from higher probability for the innermost constellation points, to lower probability for the outermost constellation points), resulting in probabilistic shaping of the constellation. Probabilistic shaping can be applied to any constellation type, including 64QAM constellation as shown in Figure 5, with a non-equally probability distribution of the individual constellation points: the inner constellation points carrying a lower energy are used with higher probability while the outer constellation points carrying a higher energy are used with lower probability.

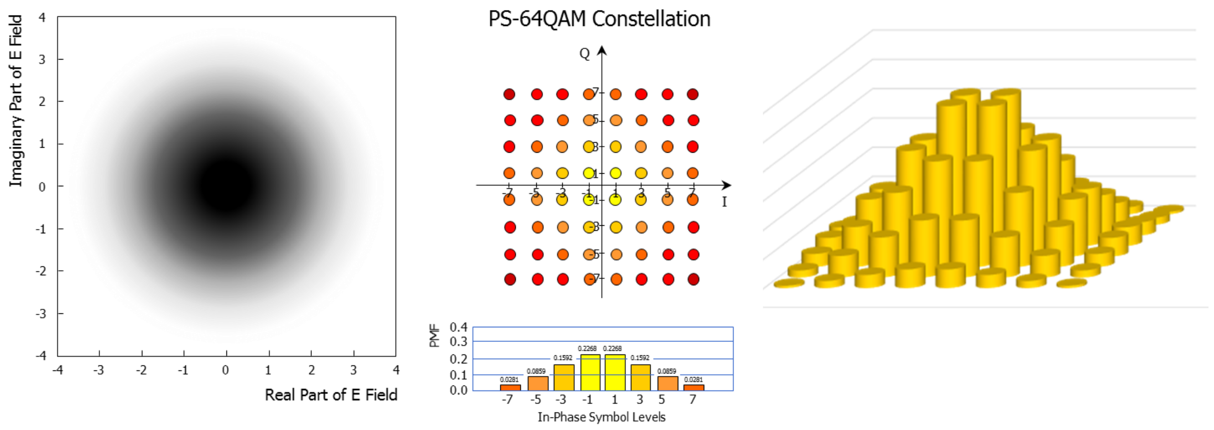

Figure 5: 64QAM signal with probabilistic constellation shaping

Geometric Constellation Shaping

Geometric shaping employs a **uniform distribution** (i.e. equiprobable symbols) on **non-equidistant constellation points**; this represents a change in the standard square 2^mQAM constellation. In Geometric Shaping (GS) constellation (like the GS-64APSK modulation represented in Figure 6), the symbols are by definition not uniformally spaced across the constellation. APSK stands for Amplitude and Phase-Shift Keying or Asymmetric Phase-Shift Keying. The in-phase symbols depend on the quadrature symbols and there is no independent processing of in-phase and quadrature symbols; geometric shaping usually results in more complex modulation and decoding schemes contrary to probabilistic shaping which is based on pragmatic square QAM modulation scheme.

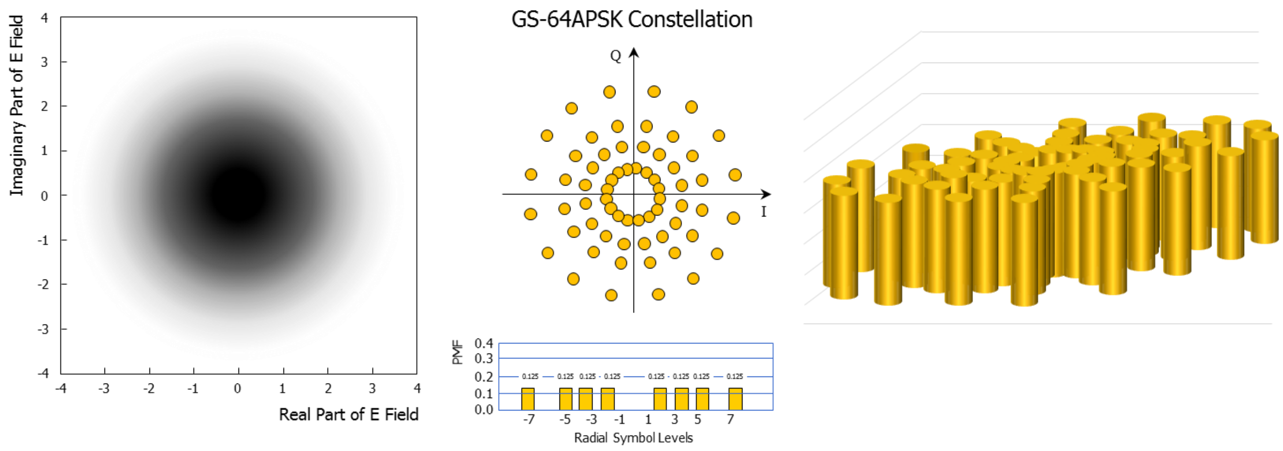

Figure 6: GS-64APSK signal with geometric constellation shaping

Hybrid Constellation Shaping, Best of Both Worlds?

Some experimental works were based on constellation shaping done both geometrically and probabilistically. In a TE SubCom paper presented at OFC 2017 conference (70.4 Tb/s Capacity over 7,600 km in C+L Band Using Coded Modulation with Hybrid Constellation Shaping and Nonlinearity Compensation, by J. -X. Cai et al.), 56APSK constellation was used (Figure 7). In addition to the geometric shaping, which is achieved by selecting a particular ring-based constellation and optimizing the radii of the 4 rings, probabilistic shaping is used as well. This is visible in Figure 7 where the yellow symbols are the most likely to be transmitted while the red symbols are those that are the least likely to be transmitted. Given that the shaping is done both geometrically and probabilistically, this constellation shaping is referred as Hybrid Shaping (HS), with non-uniform distribution (i.e. non equiprobable symbols) on non-equidistant constellation points.

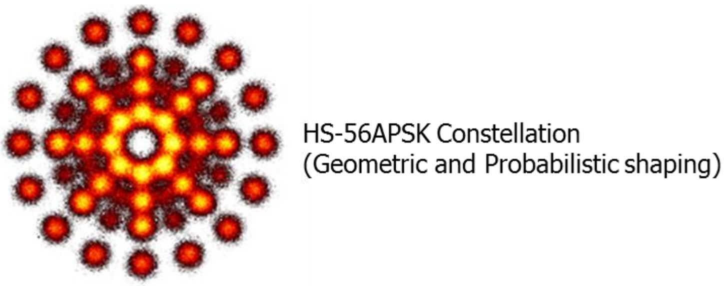

Figure 7: 56APSK constellation mixing geometric and probabilistic shaping

High Spectral Efficiency Laboratory Demonstrations

This section lists a selection of lab experiments about long-haul, ultra-high-capacity transmission along subsea cable systems reported in technical conferences or published in peer-reviewed technical journals since the beginning of year 2017:

- 34.9 Tbit/s fiber capacity at 8.3 bit/s/Hz over 6,375 km, using C-band EDFA (NEC)
- 70.4 Tbit/s fiber capacity at 7.23 bit/s/Hz over 7,600 km, using C+L EDFA (TE SubCom)
- 65 Tbit/s fiber capacity at 7.3 bit/s/Hz over 6,600 km, using C+L EDFA (Nokia Bell Labs)
- 24.6 Tbit/s at 5.9 bit/s/Hz over 10,285 km, using C-band EDFA (ASN)
- 51.5 Tbit/s at 5.29 bit/s/Hz over 17,107 km, using C+L EDFA (TE SubCom)

Field Trial Demonstrations

In parallel to lab demonstrations, we have seen several field trials during the first three quarters of 2017 aiming at assessing the upgrade capacity performance of long-haul subsea cable systems that were designed 2 to 4 years ago, with C-band repeaters:

- 17.2 Tbit/s fiber capacity at 4 bit/s/Hz over 5,523 km (AEC-1 subsea cable system), by Nokia Bell Labs / Facebook
- 19 Tbit/s fiber capacity at 4.3 bit/s/Hz over an unnamed “modern transatlantic route”, by Infinera
- 4.0 bit/s/Hz over 10,940 km (FASTER subsea cable system), by Google / NEC / ASN
- 18.2 Tbit/s at 4.5 bit/s/Hz over 10,500 km (Seabras-1), by Infinera

To Conclude with a Few Thoughts

For the current subsea cable system design in commercial service, it looks like that the objective is to operate these submarine cable systems at the limit of the optical power regime where the nonlinear effects become noticeable, with an optical signal-to-noise ratio of about 13 dB/0.1 nm.

Nyquist pulse-shaping and ultra-high wavelength stability enable to decrease the channel spacing down to the baud rate (for instance, if the optical carriers are modulated at the speed of 49 Gbaud, the carriers can be spaced 50 GHz apart). Starting from this remark, the game for increasing the fiber capacity becomes very simple. Assuming that C+L EDFA optical amplification offers a maximal spectrum of 10 THz, and that today's commercially-available electronics speed is 50 Gbaud, the game is then to split the 10 THz optical bandwidth into 50 GHz slots and to find a way to maximize the capacity transmitted within in each of these 50 GHz slots. As an illustration, the work reported Nokia Bell Labs in the April 2017 issue of the Journal of Lightwave Technologies achieved an average net data rate of 363.1 Gbit/s per 50 GHz slot! This must be compared with the customary practice of placing one 10 Gbit/s carrier on a 50 GHz grid 10 years ago…

As technology is getting closer to the Shannon limit, the options identified for the short- to mid-term for further increasing the total subsea cable system capacity are wider repeater bandwidth and/or higher fiber count.

Biography

Bertrand Clesca is delivering advice/consultation/consultancy with OpticalCloudInfra for optical infrastructure planning/acquisition/development.

Bertrand has thirty years of experience in the optical telecommunications industry, having held a number of research, engineering, business development and sales positions in both small and large organizations.

Bertrand holds an MSC in Physics and Optical Engineering from Institut d'Optique Graduate School, Orsay (France), an MSC in Telecommunications from Telecom ParisTech (fka Ecole Nationale Supérieure des Télécommunications), Paris (France), and an MBA from Sciences Po (aka Institut d'Etudes Politiques), Paris (France).