Why is the fate of the G.654.E fibre fundamentally different from that of the G.653 and the G.655 fibres?

A lesson from the past, a solution for the future.

ACOME GROUP

In a context of exponentially increasing bandwidth demand, long-haul optical networks face unprecedented challenges.

Historically, cabling infrastructure development has been driven by innovation, with each new generation of optical fibre pushing the boundaries of transmission. However, the rapid pace of technology and the rise of digital signal processing have highlighted the obsolescence of some legacy solutions, such as G.655 fibre. This document examines why legacy fibre types no longer meet the demands of modern long-haul terrestrial networks and introduces a new generation of fibres, in particular G.654.E. We will see how, in complementarity with technological advances in the active layer, this fibre offers a sustainable and long-lasting solution to optimise total cost of ownership and meet tomorrow's bandwidth requirements.

Strategic importance of selecting optical fibre

Contrary to common belief, a network is not static; it constantly evolves through regular updates. Upgrades to civil engineering infrastructure and cabling are far more expensive than upgrades to electronic equipment and software[1].

That is why selecting the right optical fibre — the network's core component — is critical. It must allow future bandwidth increases, especially on long-haul networks that aggregate data streams demanding ever higher throughput. The optical cable must be able to accommodate this ongoing increase in bandwidth so as to ensure long-term return on investment over decades

An optical fibre's capacity is constrained by a trade-off between data rate and reach.

In optical telecommunications, per-wavelength transmission rates have surged dramatically. While they climbed from 10 Gb/s to 40 Gb/s over one decade (1990s to 2000s), they jumped from 200 Gb/s to 1.6 Tb/s in the last decade. This increase stems from the fast deployment of new technologies to meet growing transmission capacity demands. However, an optical fibre's capacity is constrained by a trade-off between data rate and reach. Factors like attenuation, dispersion and nonlinear effects reduce the optical signal-to-noise ratio. Over time, fibre-optic technologies have evolved to add value by compensating for certain signal degradations.

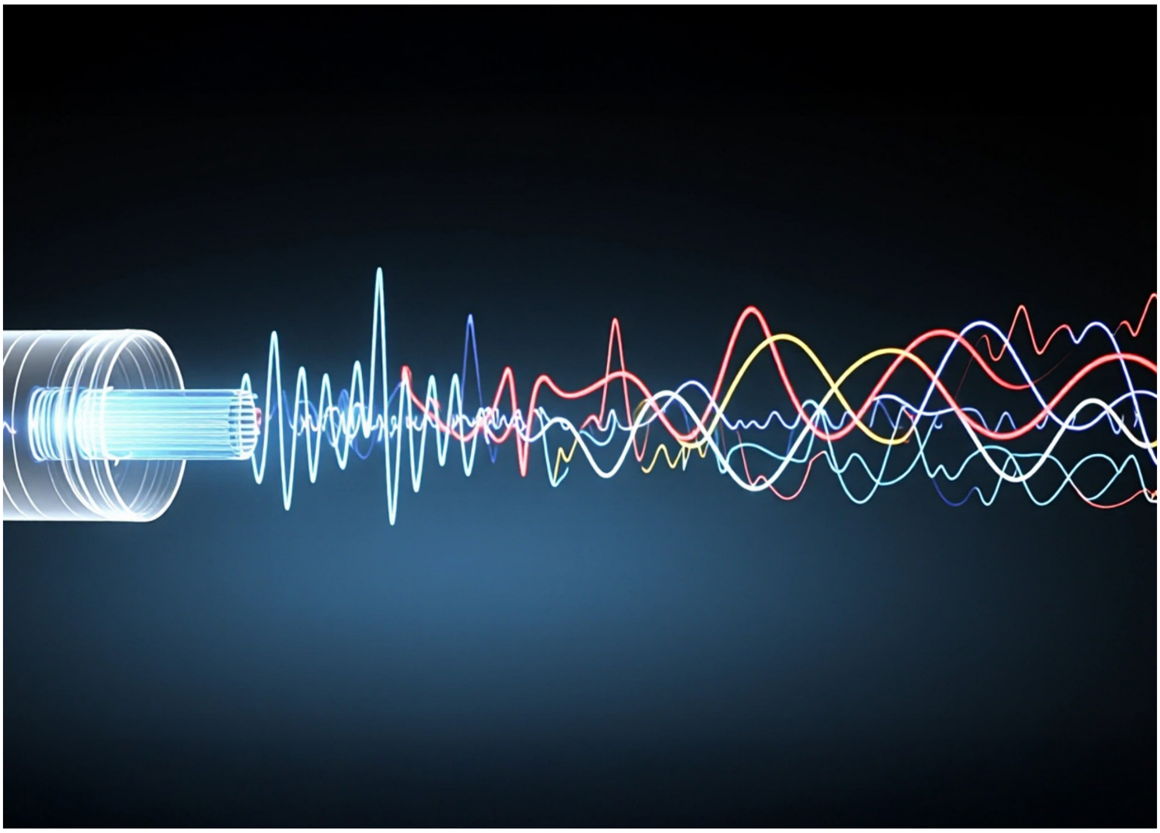
1 https://europacable.eu/wp-content/uploads/2021/01/Europacable-Guide-Expected-Life-Time-of-Passive-Optical-Infrastructure-21-Oct-2020.pdf

Multiple fibre generations to compensate dispersion issues

For transmission rates of a few Gb/s up to tens of Gb/s, optical encoding was done by simple intensity modulation, using formats such as OOK (On-Off Keying). At these bitrates, the high chromatic dispersion of standard G.652.D optical fibres caused significant signal degradation, thus limiting transmission distance.

Indeed, G.652.D fibre exhibits high chromatic dispersion (around 17 ps/nm·km) in the 1550 nm window, causing pulse broadening and limiting throughput and reach unless complex dispersion compensation is applied. This dispersion was problematic, particularly when trying to take advantage of the low linear losses in the C-band for long-haul networks. Due to this high dispersion, G.652.D systems had to include compensating modules or fibres, increasing the complexity and cost of long-haul networks.

That is why, to preserve signal quality over longer runs, it has become advantageous to use dispersion-shifted fibres (G.653 and G.655), engineered to minimise this effect.



G.653 fibre
Characteristics and constraints for WDM networks

G.653 fibre, also known as Dispersion Shifted fibre (DSF), is a single-mode fibre originally engineered for long-haul networks. Its main feature is the shift of its zero chromatic dispersion point towards the 1550 nm window, where signal attenuation is lowest. This offset enabled very long-distance transmission at high bitrates using a single wavelength. However, this design quickly made G.653 unsuitable for evolving network requirements. From the 1990s onwards, networks began widely deploying wavelength-division multiplexing (WDM) technologies. Zero dispersion at 1550 nm significantly increases the nonlinear effects. This unwanted effect generates new wavelengths that interfere with the original WDM channels, causing crosstalk and significant signal degradation. For this reason, G.653 fibre was quickly superseded by G.655 fibre, which has low but non-zero dispersion.

G.655 fibre
Design and deployment for long-haul WDM networks

Developed in the 1990s, G.655 fibre (also known as Non-Zero Dispersion Shifted fibre, or NZDSF) was specifically engineered to meet the demands of long-haul WDM networks. Unlike G.653, this fibre exhibits a low non-zero dispersion in the 1550 nm window (typically around 4 to 8 ps/nm·km). This technical feature substantially reduces nonlinear effects while keeping dispersion low enough to limit signal broadening.

G.655 thus became the go-to solution in the 1990s–2000s for dense wavelength division multiplexing (DWDM) systems and high-capacity long-haul transmission. Initially, it was optimised for per-channel rates of 2.5 to 10 Gbit/s, with the option of reaching 40 Gbit/s on specially tuned systems. It therefore reached its peak with widespread deployment in long-haul WDM networks.

Despite its success, the rapid rise in network bitrates has exposed the limits of G.655 fibre. The emergence of new coherent-optics technologies, particularly improvements in digital signal processing, has made it possible to mitigate dispersion-related limitations.

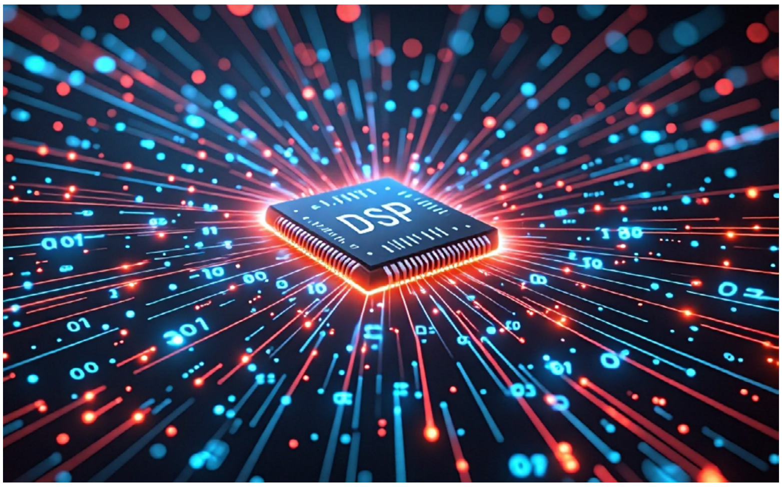
The obsolescence of G.655 fibre in the era of coherent optics

The main reason G.655 became obsolete was the emergence of new technologies around 2010, notably coherent transmission and advances in digital signal processing (DSP). Coherent optics is an optical communication technology that, by encoding information on the phase and polarization of light as well as its intensity, enables far higher data throughput and improved spectral efficiency, and in particular allows digital compensation of signal impairments over very long distances.

These innovations have fundamentally altered the landscape. The introduction of coherent technology, used in DWDM systems with per-wavelength transmission capacities ≥ 100 Gb/s, has effectively removed chromatic dispersion as a factor affecting transmission quality. Therefore, the G.655 fibre was no longer required. Indeed, with the surge in data rates and the advent of coherent systems, the small but non-zero dispersion of G.655 fibre has become unnecessary and can even be a limiting factor. Phenomena such as polarization mode dispersion (PMD) and other nonlinear effects re-emerge at these high bit rates, impacting network capacity and reliability.

Digital signal processors can now electronically and efficiently compensate for dispersion and non-linear effects, a function originally intended for G.655 fibre. The paradigm has shifted: fibre is no longer the fix for dispersion issues — it's now handled by electronics and software. For ultra-high bitrates (>100 Gb/s), higher dispersion has actually become preferable, as it enables more effective digital compensation without requiring a complex network architecture. In summary, G.655, once an innovative solution, is no longer suited to the flexibility and scalable capacity demands of modern optical networks.

DSP capabilities: a driver for the expansion of ultra-high-speed networks



DSPs marked a shift in optical communications by converting rigid, costly analogue signal processing into a flexible, powerful digital solution. These electronic chips function as the control unit of optical transponders, electronically compensating signal degradation over long distances, thereby reducing frequent, costly optical regeneration.

The main benefits of using DSPs are:

- **Signal impairment correction:** DSPs digitally compensate for fibre effects such as chromatic dispersion and nonlinearities, thereby optimising transmission reach and throughput.
- **Capacity increase:** They use advanced modulations (e.g. 16QAM, 64QAM) to encode more data per optical pulse, enabling very high throughputs (1.6 Tb/s and above in future).
- **Improved reliability:** Using forward error correction (FEC), DSPs rebuild lost data and improve the signal's tolerance to optical noise.

The integration of DSPs, combined with WDM technologies, was a major breakthrough, enabling networks to handle the exponential surge in data traffic during the 2000–2020 period. These technologies significantly increased throughput during that period.

However, this approach now faces new limits: we are reaching Shannon's limit, the theoretical maximum capacity of a transmission channel. To keep boosting bandwidth, it's now necessary to rethink network architectures and explore new solutions beyond just digital signal optimisation.

Shannon limit: the glass ceiling of DSPs

The Shannon limit is a fundamental theoretical boundary that defines the maximum bit rate a communication channel can support (C in bit/s). It depends on the channel bandwidth (B in Hertz) and the signal-to-noise ratio. A higher signal-to-noise ratio therefore allows data rates to be increased.

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

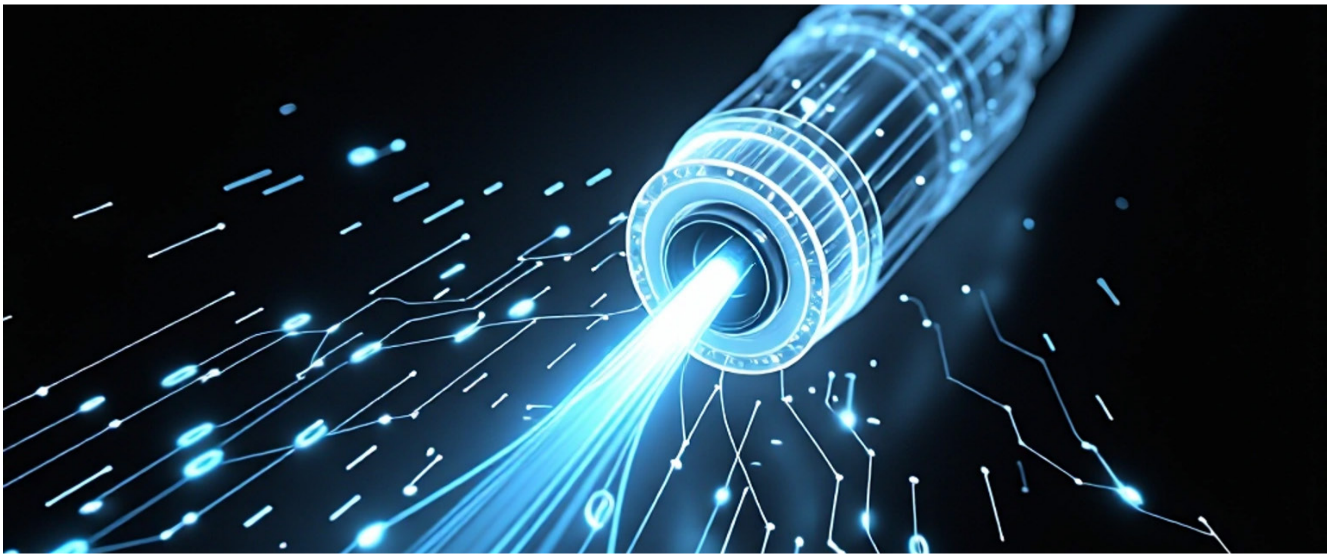
In optical communications this limit is a hard physical boundary: even with the most advanced algorithms and modulation techniques, it cannot be exceeded. Shannon's limit sets an absolute cap on how much information can be sent, even when using error-correcting codes or advanced modulation schemes. DSP play a key role by digitally compensating signal impairments (dispersion, noise, non-linear effects, etc.) to approach it. The more powerful the DSPs, the closer you can get to that threshold. However, there is also a «development limit» for DSPs, where increasing their complexity no longer yields meaningful throughput or signal-quality improvements, or does so only at prohibitive cost or latency. In short, Shannon's limit remains the ultimate physical barrier that signal-processing technologies continually strive to approach.

Beyond Shannon's limit and DSP development constraints, it's essential to go beyond mere signal optimisation. The answer to rising bandwidth demand now lies in a new approach: redesigning cabling architecture and adopting enhanced optical fibres that inherently improve signal-to-noise performance, engineered for next-generation ultra-high-speed networks.

To exceed 800 Gb/s per channel, the choice of optical fibre is strategic because it directly affects the key capacity drivers from Shannon: usable bandwidth, optical signal-to-noise ratio, and transmission distance without regeneration.

G.654.E: value-added fibre pushing Shannon's limit

In response to the Shannon limit nearing and DSP constraints, the G.654.E fibre emerges as the value-added fibre solution for next-generation networks at 800 Gb/s per channel and above, thanks in particular to its pure silica core.



Indeed, doping in optical fibres involves adding specific chemical elements into the fibre core to alter its optical properties, chiefly the refractive index, thereby enabling light guidance. However, this doping can still negatively affect the fibre's linear attenuation. G.655 and G.652.D fibres have a germanium-doped core, which improves certain properties but results in higher intrinsic attenuation than pure silica fibres. Conversely, G.654.E fibre uses an undoped pure silica core, which significantly lowers linear attenuation and therefore delivers improved optical performance.

Key advantages of the G.654.E are:

- **Ultra-low attenuation:** With optical attenuation below 0.16 dB/km, this fibre keeps the signal quality high over very long distances. This keeps a high optical signal-to-noise ratio, a critical parameter that, per Shannon's formula, raises the channel's theoretical capacity.

- **Large effective core area:** The enlarged core of the G.654.E lowers light intensity within the fibre, significantly reducing the nonlinear effects. By reducing such impairments, it provides a more linear transmission channel—ideal for complex modulations—and lets DSPs correct errors far more efficiently.

Germanium is a strategic but critical element due to supply risks and high price volatility. Germanium's critical status stems from its highly concentrated production in China (more than 60% of global supply) and the fact that it is only a by-product of the extraction of other metals (zinc or coal). This geographical dependence, exacerbated by the risk of export restrictions for geopolitical reasons, makes its supply fragile. The use of G.654.E fibers, with a pure, undoped silica core, is therefore a major asset in reducing this geopolitical and economic dependence in network deployment.

- **Optimization for coherent systems:** By minimising loss and non-linear effects, G.654.E is ideal for very-high-capacity coherent optical transmission systems (>800 Gbit/s per wavelength) that use higher-order modulation formats (QPSK, 16QAM, 64QAM, ...). It enables full use of next-generation DSPs and their advanced error-correction algorithms.

For technical details on this fibre's physical properties and its suitability for very-high-capacity coherent optics, please refer to our dedicated white paper.[1]

Designed to complement the strengths of modern DSPs, G.654.E fibre offers ultra-low attenuation and a large effective area, improving signal-to-noise ratio and thus extending capacity limits by acting on the physical transmission characteristics.

Optimisation and long-term reliability: How G.654.E fibre lowers the total cost of ownership for long-haul networks.

By deploying G.654.E fibre, operators rely on a technology that fundamentally increases the maximum throughput carried over their infrastructure. They therefore invest in the longevity of their cabling infrastructure, ensuring long-term return on investment and a significant reduction in total cost of ownership. In practical terms, the fibre's intrinsic properties — low attenuation and large effective area — mean that repeater spacing can be extended, simplifying network architecture and cutting costs. On high-capacity long-haul links, this fibre can, in some use cases, allow reducing or even completely eliminating the need for regenerators, a major benefit for network CAPEX and OPEX.

G.654.E fibre also removes the need for complex amplifiers such as Raman amplifiers on long-haul links. Although these provide better amplified spontaneous noise performance than EDFAs, their deployment and upkeep are costly and complex. Installing Raman amplifiers typically requires physical access to the fibre at the end of a span (which may be restricted by contract), qualification of the fibre over the first few kilometres to maximise optical gain and entails higher power consumption.

Unlike G.655 fiber, which was designed to solve technological problems, G.654.E fiber offers better performance with regard to the fundamental limitations of networks.

1 https://www.acome.com/sites/default/files/inspirations/pdf/whitepaper-g654e_bd.pdf

G.654.E fibre, with its superior optical performance, delivers better spectral efficiency, improved optical margins and therefore greater resilience. It also allows longer spans between amplifiers, lower energy consumption in Watts per Tb/s transmitted, and higher equipment density in terms of rack units per Tb/s.

> G.654.E fibre therefore delivers significant operational and cost simplification for long-haul terrestrial links compared with conventional G.652.D fibre solutions paired with Raman amplifiers. This technical approach results in a simpler, more flexible and cost-effective network architecture, while delivering unmatched capacity and reach.

A sustainable technology value proposition

Some may wonder whether G.654.E fibre will meet the same fate as G.655. However, history does not repeat itself exactly. Unlike G.655, which was developed to address issues in 1990s transmission technology (with constraints not fully understood back then), G.654.E is a fibre inherently designed for current and future network challenges — namely approaching the Shannon limit and the limits of digital signal processing technologies. It is not a temporary workaround but a long-term foundation that complements the most advanced DSPs. Choosing G.654.E is therefore an investment in a future-proof technology that meets long-term capacity requirements.

The G.654.E: A resilient foundation for next-generation networks

Optical fibre is not a static asset but the core of a network that continuously evolves. With traffic rates rising exponentially, legacy solutions like G.655 fibre have become obsolete.

Today, DSP improvements let us optimise transmission performance, but we now face the Shannon limit, a physical ceiling that even the most advanced DSPs cannot surpass. To further increase network capacity, we must rethink our approach and work directly on the medium itself: optical fibre.

This is where G.654.E fibre provides a long-term, strategic solution. Thanks to its unique properties — ultra-low attenuation and a large effective core area — it inherently boosts optical performance and reduces the physical limitations of the medium. This fibre enables equipment and DSPs to operate close to the Shannon limit, supporting data rates above 1.6 Tb/s per wavelength over long distances.

Unlike G.655, G.654.E is not a compensation technique but an intrinsically higher-performance technology. For long-haul backbone links and data-centre interconnects, where every gain in signal-to-noise ratio matters for maximum throughput, G.654.E is the most sensible investment. It not only delivers maximum capacity and reach but also ensures an optimised total cost of ownership for future bandwidth upgrades.

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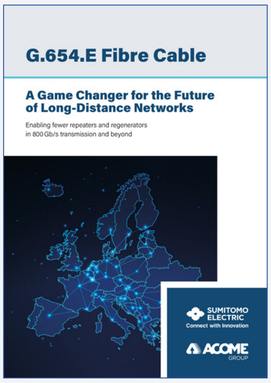
Combining a master's degree in engineering from ENSSAT and a doctorate in physics with a strong background in ICT. His experience spans research at the French National Centre for Scientific Research (CNRS) and product line management within telecom equipment manufacturing. Since joining ACOME as France Marketing Manager in 2021, he leverages his ICT expertise in optics and telecommunications to drive the development and commercialization of sustainable optical cables.



Discover our White Paper, co-authored by ACOME and Sumitomo Electric, on the future of optical networks!
As the explosion of data traffic (AI, Cloud, streaming) pushes systems to 800 Gb/s and beyond, conventional G.652.D fibers are approaching their physical limits over long distances. Our study explores how G.654.E fiber—thanks to its larger Mode Field Diameter (MFD) and ultra-low attenuation—drastically improves performance in terms of throughput and reach, and reduces operating costs by requiring fewer repeaters and regenerators.

Download the white paper to learn about the solutions that will take your cabling infrastructure to the next level for a scalable and sustainable network!

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