ARE THERE ENOUGH SUBSEA CABLES?

BY BERTRAND CLESCA AND PHILIP DEGUZMAN

When we look at the current state of optical fiber transmission technologies, we may feel as if it is a never-ending journey towards greater optical transmission capacities – especially within fiber optic submarine cable systems. The past three decades have brought with them several technical breakthroughs, beginning with the introduction of optical amplification into submerged repeaters, followed by the advent of optical wavelength multiplexing and optical coherent transmission technology. Most recently, we've seen a significant increase in fiber count. These milestones have greatly enhanced the capability of submarine fiber optic cable system technology to meet the insatiable traffic demands of the world's population, and it must not be taken for granted.

If we take a closer look at the historical evolution of subsea fiber optic cable capacity and what is coming in the short term, the situation undoubtedly looks less rosy. The latest cable systems have the ability to transport more capacity than their predecessors, but the new challenge for system designers is the shrinking gap towards the fundamental Shannon limit, which places an upper limit on per-fiber capacity, and the practical electrical and mechanical limitations that coincide with respecting this limit. This situation raises a simple question: Can foreseeable evolutions in cable technology handle forecasted traffic demand growth rate?

This article will focus on trans-Atlantic cable systems for two reasons. First, the trans-Atlantic route is traditionally where the newest cable technologies have been introduced over the past 150 years. Second, it offers superior cable capacity than the other trans-oceanic routes, due to its moderate length and strong pressure to minimize the cost per transported bit.

AN OVERVIEW OF TRANS-ATLANTIC CABLE TECHNOLOGY EVOLUTION

The saga of trans-Atlantic cable systems started in 1858 with the short-lived deployment of a telegraphic cable system between Ireland and Newfoundland that operated for only three weeks before ultimately failing due to a number of mounting issues. This first trans-Atlantic cable did, however, send a total of 732 messages during its fleeting lifespan. The inaugural celebratory message, sent by Queen Victoria to U.S. President Buchanan, took more than 30 hours to be transmitted! The message read: "England and

America are united. Glory to God in the highest, and on Earth, peace, good will toward men." The transmission speed never exceeded one word per minute.

While a failed, yet still encouraging undertaking, engineers would build on it to improve the cable design and technology, eventually offering higher capacity and longer lifetimes. The TAT-1 (Trans-Atlantic No. 1) cable system between Scotland and Newfoundland was the first trans-Atlantic telephone cable system based on coaxial cable technology. TAT-1 was put into commercial service in 1956, initially carrying 36 telephone channels before being upgraded to 72 channels in 1960. In its first 24 hours of public service, there were 588 calls from London to the U.S. and 119 calls from London to Canada.

The next subsea cable breakthrough occurred following two major inventions in the 1960s and early 1970s. These were the availability of compact semiconductor lasers operating at room temperature, and the use of optical fibers offering low attenuation at wavelengths where semiconductor lasers emit light. With the use of these technologies, the TAT-8 cable system entered into commercial service in 1988. TAT-8 utilized 1300 nm single mode fiber and 280 Mbits/s transmission technology. The very next trans-Atlantic cable entered into commercial service in 1991 and doubled the transmission rate of TAT-8 by operating at 560 Mbit/s per fiber in the 1500 nm optical window, where optical fiber attenuation was (and still is) minimal.

The TAT-8 through TAT-11 cable systems also relied on electrical regeneration, which took place within undersea bodies known as "repeaters." Electrical regeneration is the process by which the optical signal along a fiber is converted into an electrical signal in order to restore its original characteristics, which may have been degraded as the signal traversed the fiber span. The electrical signal is then reconverted into an optical signal as it continues towards the next repeater and its final destination.

The next technological innovation occurred in 1996 with the operation of the TAT-12/13 cable systems. Both of these cables introduced optical amplification within the undersea repeaters. Unlike the previous generation of repeaters, which centered around electrical regeneration, the TAT-12/13 repeaters employed optical amplification. Repeaters utilizing optical amplification can process multiple modulated optical carriers at the same time and are

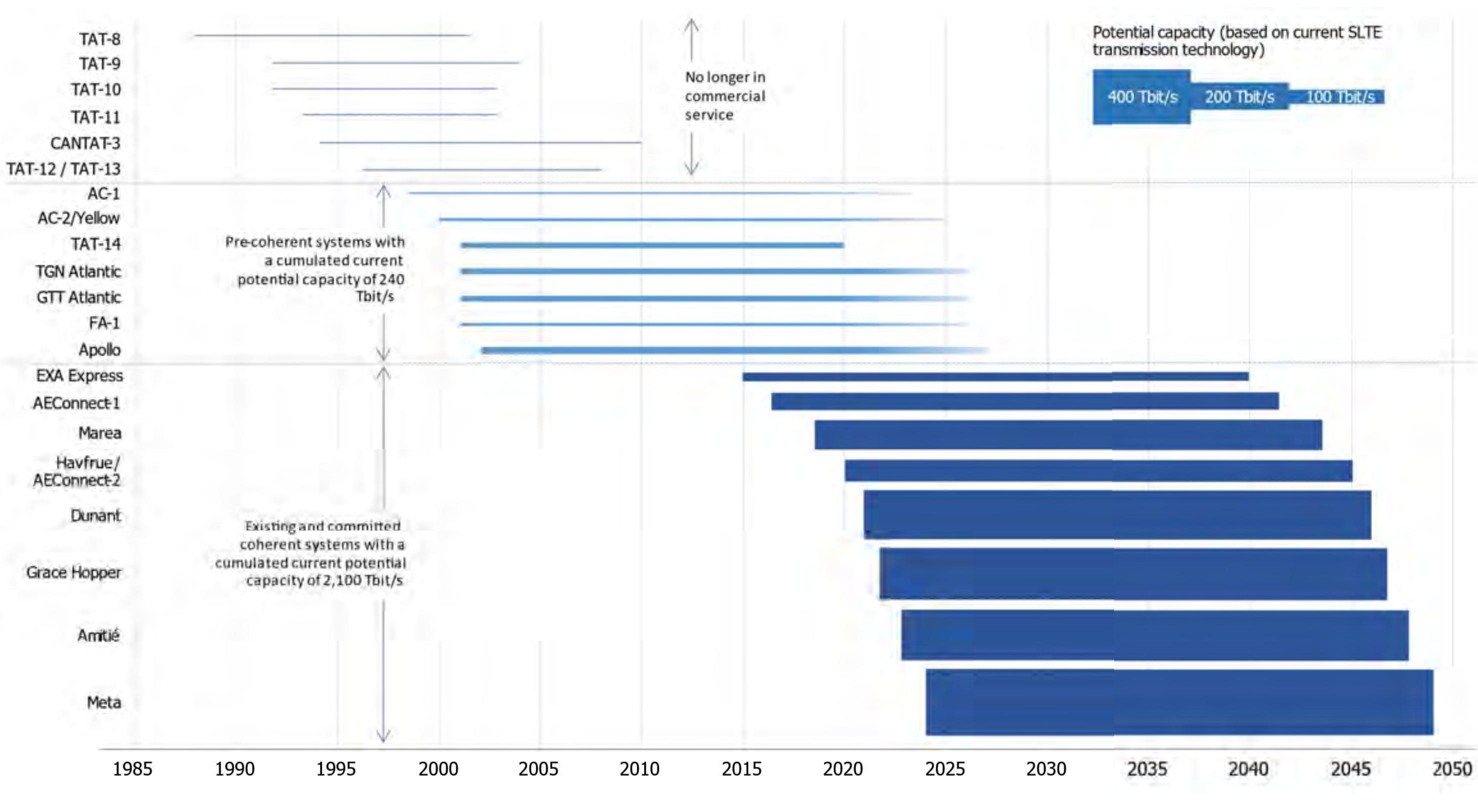

Figure 1: Evolution of Cross-Sectional Cable Capacity across the Atlantic Ocean

bit-rate and protocol-agnostic, allowing for upgrades with higher-speed transmission equipment when made available during the lifetime of the cable system.

A number of technical evolutions would carry the industry for almost two decades. However, it wasn't until the mid-2010s when the industry saw the first trans-Atlantic cable systems (i.e., EXA Express and AEC-1) designed for use with optical coherent transmission technology. Although coherent transmission techniques were introduced in radio-based communication systems a few decades earlier, the ability to adapt this technology and enable its use for undersea systems was a significant achievement. It provided a boost in per-fiber capacity by a factor of approximately 10 when compared to previous generations of transmission technology.

One last characteristic to keep in mind is the total number of fibers within an undersea cable. To enable bidirectional transmission, two fibers are required, which is known as a "fiber pair." While the number of fiber pairs within a cable system started at two and eventually grew to eight, it was not until 2021 that cable system designs could accommodate more than eight. Trans-oceanic systems today are able to support up to 24 fiber pairs (or more in the near future).

INCREASES IN TRANS-ATLANTIC CABLE SYSTEM CAPACITY

To assess the pace at which trans-Atlantic cable capacity has increased, we need to look at the per-fiber capacity and the cross-sectional cable capacity of past trans-Atlantic cable systems. In the case of a ring architecture (with two physically separated cables between North America and Europe), we will only consider the cross-sectional capacity of one cable. In the case of "Y" design (with one landing site in North America and two in Europe), we will consider the capacity of the trunk cable between North America and the branching unit splitting the cable into two European branches.

Figure 1 below represents the cross-sectional capacity from the TAT-8 cable system to the latest announced trans-Atlantic system – a yet to be publicly named cable from Meta that will be supplied by NEC and is planned to enter into commercial service in 2024. For the cable systems that are still in service, the thickness of the horizontal bars represents a graphical estimation of the capacity achievable with current generation Submarine Line Terminal Equipment (SLTE) transmission technology.

From the TAT-8 to MAREA cable systems, significant effort has been applied to increasing the per-fiber-pair capacity, with the number of fiber pairs of these cable systems comprising anywhere between three and eight, depending on the number of co-owners and their respective business models. In order to make efficient use of the limited electrical power available to the repeaters, system designers began to increase the number of fiber pairs for the post-MAREA cable systems. This resulted in 12 fiber pairs for Dunant in 2021; 16 fiber pairs for Grace Hopper and Amitié in 2022-2023; and 24 fiber pairs for Meta's upcoming trans-Atlantic cable in 2024.

Referring back to the use of optical coherent transmission technology, a twofold impact on subsea cable system capacity unfolded. For legacy systems, new coherent SLTE technology enabled cable systems to multiply their original design capacity estimates by up to 10x. For newer cable systems (deployed since mid-2010s), a new cable system line design was adopted, which relied on an uncompensated link with highly chromatically dispersive fibers. This new line design, combined with the use of coherent SLTE transmission technology, stronger Forward Error Correction (FEC) code, denser carrier spectral packing, transmission margin optimization, and additional innovations from SLTE vendors, resulted in an original design capacity 20x higher than a pre-coherent cable system design. These advances

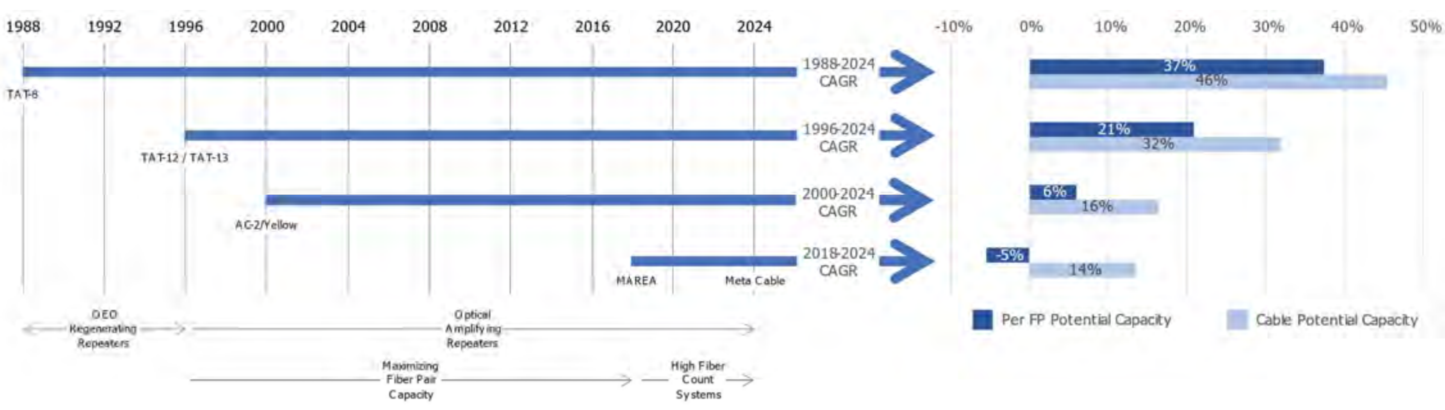

Figure 2: Capacity Growth Rate for Trans-Atlantic Cable Systems Over Four Different Time Periods

truly paved the way for cloud computing, high-definition content, and other technologies prevalent in today's society.

Interestingly enough, the design capacity for a given cable system is a figure that can significantly move over time, even for coherent systems. In 2015, the MAREA cable system was originally specified to support about 13 Tbit/s per fiber pair. Three years later, once MAREA was in commercial service, Infinera demonstrated a per-fiber capacity of 26.2 Tbit/s, before demonstrating 28 Tbit/s in 2021 (with some margin for commercial operation). If eliminating this margin, Infinera was able to demonstrate up to 30 Tbit/s per fiber pair!

When comparing this figure to the Shannon-limited capacity of about 42 Tbit/s for the MAREA cable system, as driven by MAREA's large effective area fiber and short repeater spacing, the gap to the Shannon-limited capacity is about 28% (i.e., as little as 1.5 dB) for MAREA. SLTE vendors continue to improve their subsea technology found within optical transponders, but it is clear that the ability to reduce this 28% gap with the Shannon limit even further will be expensive, and that entirely closing the gap may not realistically be achievable. Unlike what the industry experienced over a decade ago, no technical breakthrough will ever allow a subsea cable system to increase its optical fiber design capacity by a factor of 10 again.

Given this realization, system designers had to start exploring other paths to achieve higher cable capacities. From 2018 onwards, instead of trying to further increase the per-fiber capacity and compensate for high-fiber nonlinear interference inherent in this approach, designers, suppliers, and owners focused on maximizing the cross-sectional cable capacity by increasing the overall fiber count within a system. Although the increases in per-fiber capacity have slowed significantly – and have actually decreased slightly when compared to the capability of the MAREA cable system, which can support up to 20 Tbit/s across the Atlantic Ocean (a standard figure based on current transponder technology) – the net result is a continuous increase in the cross-sectional cable capacity, as shown earlier in Figure 1.

CAPACITY GROWTH RATE FOR TRANS-ATLANTIC CABLE SYSTEMS

Figure 2 illustrates at what pace cross-sectional cable capacity has been increasing over the past few decades. When looking at the first fiber optic trans-Atlantic cable system, and considering the latest expected trans-Atlantic system to enter into commercial service in 2024, cross-sectional cable capacity has increased at a 46% Compound Annual Growth Rate (CAGR).

If we focus on optically amplified cable systems (starting from the TAT-12/13 cable system), the cross-sectional cable capacity growth rate is reduced from a CAGR of 46% to 32%. If we look at the period from 2000 to 2024 and from 2018 to 2024, the cable capacity growth rate further slows to a CAGR of 16% and 14%, respectively.

If we assume the installation of a 32-fiber pair cable sys-

Table 1: Trans-Atlantic Cable Capacity vs Year per 2019 and 2022 Scenarios

Trans-Atlantic Cable Capacity vs Year	2020	2021	2022	2023	2024	2025	2026
2019 Scenario (Based on Assumptions and Predictions)							
1 – Fiber Pairs	16			32		50	
2 – Capacity per Fiber Pair (Tbit/s)	20			20		20	
3 – Cable Capacity (Tbit/s)	320			640		1,000	
4 – Number of New Cables Required – Incremental	2	1			1		1
5 – Number of New Cables Required – Cumulated	2	3	3	3	4	4	5
2022 Scenario (Based on Existing and Publicly Planned Cables)							
6 – Fiber Pairs	8	12	16		24		32
7 – Capacity per Fiber Pair (Tbit/s)	20	25	23		20		18
8 – Cable Capacity (Tbit/s) – Current SLTE	160	300	368		480		576
9 – Cable Capacity (Tbit/s) – Future SLTE	208	390	478		624		749
10 – Number of New Cables Required – Incremental	1	1	1	1	1		2
11 – Number of New Cables Required – Cumulated	1	2	3	4	5	5	7

tem in 2026, with a per-fiber-pair capacity of 18 Tbit/s, the 2024 to 2026 cable capacity growth rate would be equivalent to a CAGR of 10%. These CAGR figures show that, in spite of all the new technologies discussed thus far, the pace at which the trans-Atlantic cable system cross-sectional capacity is increasing over time appears to be inexorably slowing down.

Figure 2 also shows that the growth of per-fiber capacity is slowing on a CAGR basis. As previously referenced, since 2018 the industry is experiencing a decrease in per fiber capacity. However, this is compensated for by the increases in fiber count, which nevertheless enable an increase in cross-sectional cable capacity.

DISCONNECT BETWEEN BANDWIDTH DEMAND AND CABLE TECHNOLOGY CAPABILITY

On the bandwidth demand side, telecom market research firm TeleGeography reported a 50+% CAGR for the used trans-Atlantic bandwidth between 2015 and 2021. For the midterm, trans-Atlantic bandwidth demand is expected to grow at a CAGR close to 35% over the 2022-2027 period.

It is obvious that these numbers illustrate a clear disconnect between traffic growth rates on the demand side and cable technology on the supply side.

At the SubOptic Conference in 2019 and the PTC (Pacific Telecommunications Council) Conference in 2020, TeleGeography addressed this supply and demand discrepancy within the trans-Atlantic route and concluded that more cable systems will be required to cope with the projected demand growth rate. Assuming an aggressive potential roll-out scenario (which includes the implementation of 32-fiber-pair and 50-fiber-pair cable systems capable of transmitting 20 Tbit/s per fiber pair in 2023 and 2025, respectively), TeleGeography forecasted the need to have two new trans-Atlantic cable systems in service in 2020, one more in 2021, and one additional system in 2024.

Two years later in 2022, it is worth looking at what happened, and what is happening over the next few years, within the trans-Atlantic "seascape."

The top half of Table 1 corresponds to the scenario built by TeleGeography in 2019 to assess the number of new trans-Atlantic cables required (Lines #4 and #5) in order to accommodate traffic demand. This scenario was based not only on the forecasted traffic demand growth rate, but also on an assumed technology evolution scenario described in Lines #1 to #3.

The bottom half of the table is fed by existing cable systems (Havfrue in 2020, Dunant in 2021, and Grace Hopper in 2022) and new cable systems that have been publicly announced (Amitié in 2023, and the Meta cable in 2024). Line #8 provides an estimate of the cable capacity based on current SLTE technology, while Line #9 corresponds to cable capacity enabled by potential future SLTE technology.

The 2022 scenario confirms the 2019 vision: More cable systems are required (and have been built) to meet bandwidth demand. The 2019 scenario, however, may have been reliant on a technology evolution that appears to have been slightly too aggressive, as this scenario underestimates the number of new cables required in 2026 by 28% (and overestimates technology improvement in the subsea industry).

The submarine cable industry may need to accept that current and future system technologies may not be able to offer the required increases in capacity to meet the needs of expected bandwidth demand growth rate over the next several years. This discrepancy in the supply and demand growth rate can be solved by:

1. Building more cable systems to stay ahead of bandwidth demand needs.
2. A profound electrical, mechanical, and/or optical redesign of subsea cable systems to enable packing and powering more fiber cores and optical amplifiers (such a redesign may not be available for another five to 10 years).
3. A radical modification within the content delivery chain.

With regards to the content delivery chain, this cannot be achieved by simply building more caching locations near Internet end-users. The development of numerous caching locations over the past two decades has not prevented the trans-Atlantic traffic to grow at a 35+% CAGR. This means that an increased supply in submarine cables is likely the best path forward for the industry to address growing bandwidth demand across the Atlantic Ocean, at least over the next three to five years.

Internet demand will only continue to increase. The industry must act swiftly if we are to keep pace. STF

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