Building a submarine network for offshore applications

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Abstract- **Building a submarine network is a challenging endeavor since it encompasses many different areas of expertise as well as a broad range of hardware and network management tools. Of course, great store must be paid to the overall cost base to ensure that the system ownership cost is minimized over its life cycle. The key parameters are generally bandwidth flexibility, network reliability and costs.**

As far as the offshore communication market is concerned, the prime candidate for system architecture will likely be that of an unrepeatered system. This paper is a three-pronged introduction to unrepeatered systems as it pertains to the offshore market. The main applications will be described as well as some similarities to terrestrial systems. Then the current state-of-art systems will be reviewed along with their hardware breakdown structure with the main insights into the technological, environmental and cost challenges involved in putting it all together.

Finally, some key components such as the cable, the cable installation and maintenance and the transmission equipment will be further analyzed and discussed in order to give the reader an understanding of the submarine infrastructure performances and cost tradeoffs.

I. INTRODUCTION

By definition, unrepeatered systems do not include repeaters and therefore do not require electrical power feeding equipment nor submerged electrically active components. All the active components are located with the transmission equipment or so called "dry" plant.

The advent of high power lasers and optical amplification has allowed unrepeatered systems to make rapid technical progress over the last couple of years. Unrepeatered systems can now be commercially equipped with WDM technology while the available channel bit rate can routinely achieve 2.5 Gbit/s or 10 Gbit/s. Moreover, high fiber counts (up to 192 and more) combined with Dense Wavelength Division Multiplexing (DWDM) technology allow for very high transmission capabilities [1], [2].

All this commercially available, fully mature and field proven technology can also benefit the offshore applications field such as the oil and gas industry and sea deployed scientific projects.

This paper will explain how the optical technology can increase any offshore network's undersea connectivity through the optics many intrinsic capabilities: versatile bandwidth access and management, best all around reliability, very long life time, error free data transfer.

The telecom driven technological pull has brought to the fore the most effective undersea data transfer networks that can step in as a form, fit and function solution for many "non-telecom" offshore applications, even though these applications might be less "bandwidth hungry".

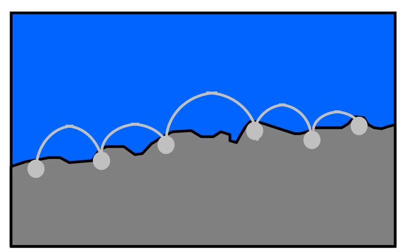
It simply suffices to under equip the "dry" plant and to optimize the cost of the "wet" plant when the bandwidth demand is not at a premium.

II. MAIN APPLICATIONS

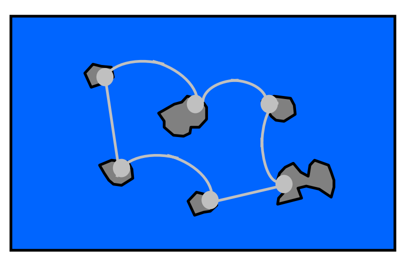
A) Traditional Telecom

Unrepeatered submarine networks can be used in several different applications:

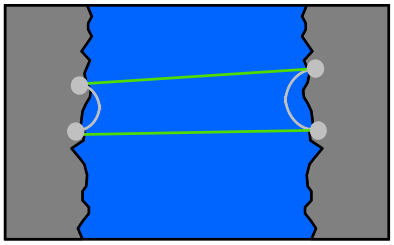
- Coastal festoon;



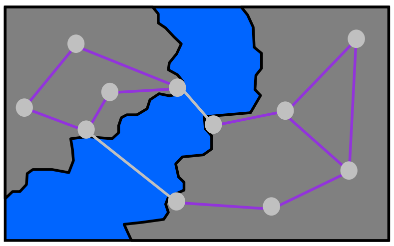
- Island ring;



- to close a transoceanic ring or as a complementary festoon to it;



- to cross submarine sections.



The main application is clearly coastal city connection, which could in many cases be alternatively achieved by using a terrestrial network.

B) Offshore industry and Scientific endeavors

The Oil and Gas industry is more and more relying on optical sub sea networks for their upstream activities. This encompasses field exploration and exploitation. In fact, the optical fiber is poised to take over as the transmission medium of choice for this industry.

There are many underlying reasons for this increasing deployment of offshore optical networks.

The platforms are being set up farther away from the shore ends so that overall the distances at stake are increasing, making use of optical communication the easiest way to bridge the gap. The communication networks have also to support a complete set of services such as data, voice, video, real time application and specialized systems. Again, only the optical technology has the intrinsic capability to seamlessly support a steady bandwidth increase from OC-3/12 to OC-12/48 in the network.

The trend is also towards unmanned platforms stemming from Health and Safety and Security of Operations requirements. It's also worth keeping in mind that the offshore labor cost is three times that of onshore labor cost. Fewer people onboard will translate into fewer trips on and off, thus sparing the environment. The net effect of unmanned platforms is that of a bandwidth increase, again calling for the optical technology. Security of Operations means very high network reliability and connectivity in such a way that the data transfer is secure, error free and that remote control can be implemented, even from Head Quarters as required or wherever the expertise may reside.
The blend of the SONET standard and of the optical technology will yield network availability above 99.999 %.

Last but not least, the optical technology is weather independent in such a way that hurricane or other disastrous displays of the earth's tantrums will not hamper proper network operation.

Scientific projects may also call for observatories where data is required to be delivered and distributed about a submerged network. Some scientific systems require multiplex transmission while others will only require single channel transmission over a high fiber count. The science might be at full ocean depths with connectivity back to shore through shallow water.

The Mars/Neptune project is a good example of a spin off application of the telecommunication optical cable for a scientific endeavor [3],[4].

C) Other alternatives

There are two other technologies available so as to establish data transfer between remote sites:

- VSAT (Very Small Aperture Terminal);
- Microwave.

VSAT cannot support real time applications since there is a latent delay for the hop to and from the satellite in geo stationary orbit. Therefore this technology is not suited to support a SONET network.

Please note that the SONET network concept will be further explained in III.C.

The microwave can support a SONET network but the distance between any two sites cannot operationally exceed 60 km.

The pros and cons of the three technologies are summarized hereafter:

Technology	Pros	Cons	Capacity
VSAT	Unlimited Reach	No real time	1.5 Mb/s
Microwave	Easy Deployment	Limited Reach (< 60 km)	155 Mb/s
Fiber	Error free, Secure	Higher entry cost	Ten's of Tb/s

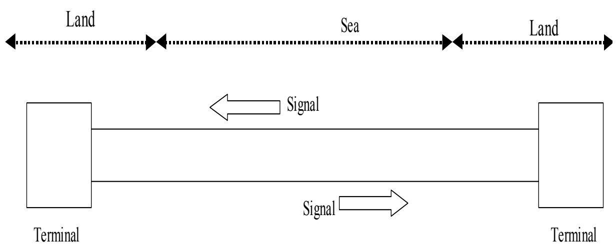
III.CURRENT STATE OF THE ART SYSTEMS

A) Unrepeatered systems overview

1) System schemes

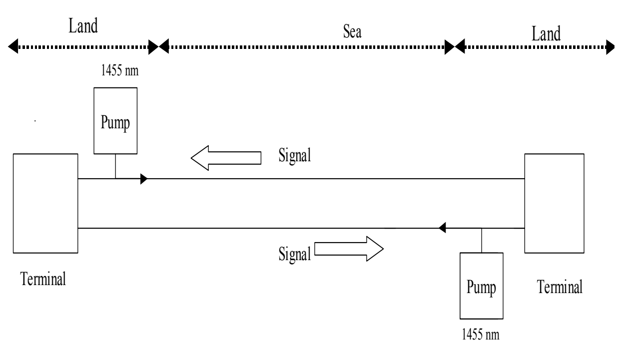
Three main schemes that will be briefly described as a starting point from which the system and hardware issues can be discussed.

- Standard



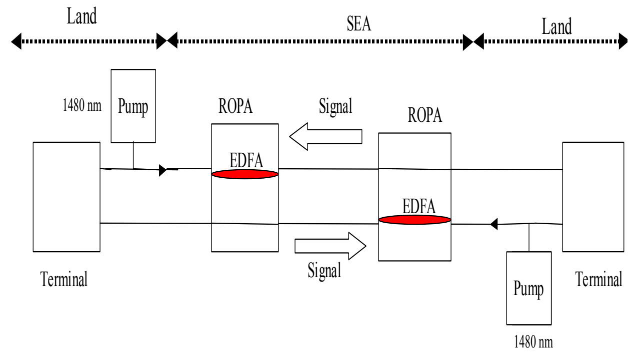
This is the simplest one. One terminal is located at each end of the link and each fiber serves one direction in order to achieve full duplex communication between the two sites. Transmission typically takes place in the 1545 nm to 1560 nm region.

- Raman Amplification



This is required when you need to implement longer spans. In this case, Raman amplification is used to extend the reach. The pump sources operate at ~ 100 nm below the transmission wavelength to create some distributed Raman gain in the line fiber in the transmission bandwidth region.

- Remote Optically Pumped Amplifier



This scheme is required in order to cope with the longest spans. The pump sources operate at 1480 nm to remotely pump the Erbium doped Fiber Amplifier loop located undersea in the ROPA (Remotely Optically Pumped Amplifier) through the line fiber. The ROPA is a plain and simple shell with optical isolators and Erbium Doped Fiber loops embedded in it. Note that these are passive components and are therefore highly reliable.

Climbing up a notch from the standard configuration to the Raman configuration will provide an 8 dB budget gain improvement while ascending an other notch to the ROPA configuration will yield a further 8 dB. This translates into a 40-50 km span increase between two schemes implementation, depending on the fiber attenuation.

- System Capacity

The system capacity needs can be met in a couple of ways as has been alluded to in the introduction. One can increase the channel count on an already lit fiber pair, light up a new fiber pair or more. Thus bandwidth flexibility is an intrinsic feature of the unrepeatered systems.

The line of reasoning necessary to select the best architecture to be implemented can be subtle and rather trying since it stems from trade-offs between:

- channel count, line rate, fiber count;
- up front budget, upgrade budget;
- operations and maintenance budget.

2) Key aspects

The schemes previously described call for a direct detection optical implementation. That is to say that the signal is simply based upon the detection of the photons energy originating from the transmitter and hitting on the receiver detector. It makes use of the transmitter brute force optical power in order to overcome the fiber attenuation and the various noises. This is why the ultimate system performances can often be described in photons/bit. So for example, the theoretical shot-noise limited sensitivity of a direct detection receiver using an On-Off keying modulation format could be 38 photons per bit for a 10^{-9} BER (Bit Error Rate) [5].

Most terrestrial systems have amplifier spans around 100 km and span losses of 25 dB whereas a submarine system will often have link lengths in excess of 300 km and span losses of 60 dB. Thus the overriding challenge is to achieve a good optical signal to noise ratio over a long stretch. This calls for high optical power to overcome optical fiber losses. And this is the first key aspect of the unrepeatered world: high optical power.

High optical power comes along with a main drawback, namely severe non linear effects that are detrimental to transmission performance. Just to name a few, some of those non-linear effects are self-phase modulation, cross phase modulation, four wave mixing and stimulated Brillouin scattering [6].

Consequently, the fiber bears an important weight on the optical power management and this is directly proportional to its effective area. The larger the fiber "core" is, the lower the optical power density will be and therefore the lower the non-linear effects threshold will be, before being too much of an hindrance to maintain good enough transmission performance. Currently the fibers used for unrepeatered systems have a 70 square micron effective area that enables transmission of up to about 21 dBm per channel @ 2.5 Gb/s.

A hint has been dropped that the fiber attenuation should ideally be kept to a minimum so as to optimize the system overall photon per bit sensitivity. As far as fiber loss is concerned, standard fiber will exhibit a 0.25 dB/km loss whereas premium fiber especially designed for unrepeatered applications can boast a 0.174 dB/km loss. That will sum up the second key aspect: fiber effective area and optical attenuation.

The third key aspect is that of the long spans which are often required for unrepeatered telecom systems. Table 1 provides a snapshot of the distances that can be offered and industrially implemented with current hardware and industry standard margins.

System Scheme	Standard	Raman	Remote
Distance @ 2.5 Gb/s	325 km	375 km	425 km
Distance @ 10 Gb/s	275 km	325 km	375 km

Table 1: Distances for unrepeatered systems (Four channel system & 5 dB system margin)

3)Trade-off(s)

Offshore networks can be optimized across a broad range of parameters by judicious tradeoffs among fiber counts, span length(s), number of wavelengths, data rate for a given desired system capability and cable routing.

In order to meet the specific requirements and economical constraints, there is a trade-off to make between fiber counts, number of channel and data rate.

From a more economical perspective, high fiber counts are not systematically the optimized solution depending on the offshore network requirements, especially for those not planning future use of dark fibers: high fiber counts can translate into higher implementation costs and operation expenses as well as difficult maintenance issues.

A nice starting point would be to have a firm grasp on the following:

- Capacity requirements at start of life;
- Capacity requirements at end of life;
- Initial budget;
- Operations and Maintenance budget.

Generally speaking, the infrastructure cost will be a major "chunk" of the whole system cost at its start of life: a rule of thumb is to consider 70 to 80 %. This infrastructure cost encompasses the cable and the marine operations to properly lay and install the cable. This will be further addressed in IV.

Managing the bandwidth will be a case of adding more equipment around an already installed line terminal equipment or to equip a new fiber pair with a new line terminal equipment. This is a typical case of pay-as-you-go and the incremental cost is somewhat minor in comparison to that of the infrastructure cost.

B) Cable and fibers

1) Fiber type

The single mode fibers typically used for unrepeatered systems will typically comply to three different ITU standards:

- G.652, "standard" fiber;
- G.654, " Pure Silica Core" fiber;
- G.655, Non Zero Dispersion Shifted fiber.

In all three cases, the fibers will exhibit a positive chromatic dispersion coefficient in the 1550 nm region. Chromatic dispersion is normally kept above 6 ps/nm.km to ensure that different channels will travel at different speeds along the fiber and that, consequently, those channels will not interact too much with one another (low cross-phase modulation, low four wave mixing).

Table 2 compares some typical data for the various large and non-large effective area bare fibers that can be used in unrepeatered applications.

In addition, the fiber macro/micro bending sensitivity is a key factor in the cable design selection. Even for the fibers that are not bend-sensitive the systems will require that the optical stability over the whole optical bandwidth is ensured. Table 3 shows the compared macrobending and microbending sensitivity of these different fibers.

2) Steel tube versus fiber characteristics

As per III.A.1) and III.B.1), the cable design has to accommodate fibers that can have very different transmission properties and/or cabling sensitivities.

- effective area (increasing to allow for higher optical power transmission and increased span);
- attenuation level (ultra-low levels required for long spans);
- chromatic dispersion (to accommodate higher bit rates and higher numbers of wavelengths).

Fiber type	Effective area (μm^2)	Dispersion @1550nm	Attenuation @1550nm
G652	80	18	0.195
G654	70	20	0.175
Large core	≥100	19 to 20	0.175 to 0.185
G655	55 to 72	6 to 8	0.210

Table 2: Fibers for unrepeatered applications

Fiber types	Macrobending sensitivity (dB/m)	Microbending sensitivity (dB/km)
G652	≈ 8	≈ 0.1
G654	≈ 0.5	≈ 0.05
Large core	≈ 2 to 10	≈ 0.4
G655	≈ 6	≈ 0.4

Table 3: Macro and microbending sensitivity at 1550nm.

In order to ensure that the benefit of using these various types of fibers is not impaired by any cabling effects, which might result in an optical loss, careful attention has to be paid in the design of the optical core. The steel tube is the industry benchmark.

The stainless steel tube fiber unit provides a stable and reliable environment for the fibers over the whole optical bandwidth. Figure 4 shows the spectral attenuation of various fiber types after the cable process, demonstrating the capability of the design to house large core fiber as well as traditional "standard" fiber. The very good optical behavior is achieved thanks to a thixotropic jelly, which acts as a buffer to the fibers, and to the stainless steel tube, which protects the fibers against any potential aggression.

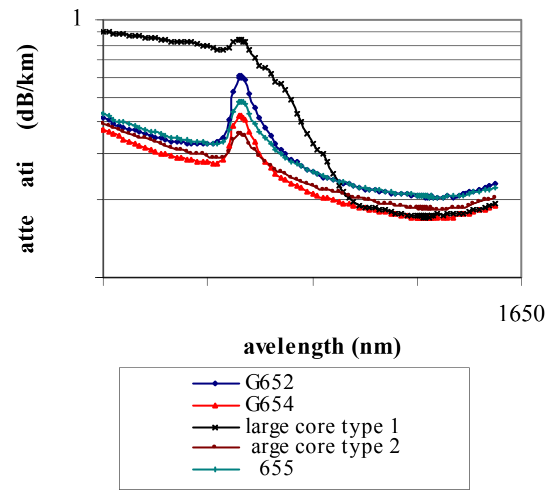


Figure 4: Cabled spectral attenuation for various fiber types.

There is an going ITU standard in place dedicated to the testing program of undersea cables [7].

C) Transmission equipment

1) SONET layer

The evolution of the communication networks through the deployment of the optical fiber as the "superhighway" has led to the rise of a new standard called SONET in the US and SDH in Europe. SONET provides for a synchronous network built around optical synchronous network elements, with a full set of standard interfaces and clearly defined layers.

The network management falls under the SONET rules and standards of operations. Therefore traffic protection is handled by the SONET layer but the protection scheme can be shared with the optical layer as well.

Broadly speaking, the optical offshore network can be conceived of as a array of SONET nodes inter linked by optical fiber: each SONET node is a communication center where data is added or dropped.

Each node in a SONET network will launch an optical signal to the SONET format in the network.

2) Optical layer

The optical layer is the optical frame which will support the transmission of the SONET optical signal. Therefore it may simply be made of passive optical equipment (such as fibers and filters) that will let the initial optical SONET signal as emitted by the SONET equipment flow through the networks to other SONET equipment.

It may also comprise some active optical line terminal equipment that interfaces with the SONET equipment in order to process and launch the initial optical SONET signal in the network. This process comprises of the following steps:

- Get the SONET optical signal in;
- Turn this optical signal into an electrical signal;
- Process it electrically as required for coding/filtering;
- Turn this electrical signal into an optical signal;
- Launch this optical signal down the optical fiber.

Then this signal will eventually reach an other line terminal equipment that will in turn reprocess and pass over error free the initial SONET optical signal to the SONET equipment (the process described above is then used backwards). This line terminal equipment is usually designed so as to enhance the network transmission capability through dual use of high optical power and forward error correction coding. This is fully transparent to the SONET network and this is also how WDM (Wavelength Division Multiplexing) is implemented: N different SONET equipment will each pass along a single SONET signal that will be processed and transmitted over a single fiber by a single line terminal equipment emitting N channels.

Therefore the SONET layer and the optical layer build on one another in order to increase the network transmission capabilities.

3) Offshore specifics

The offshore networks will usually not call for:

- very long spans in between two links (the spans will often be limited to < 250 km)
- high data rate (the data rate requirements will often be limited to < OC 48)

It is also not unusual to dedicate one fiber pair for each network application. For example, the oil and gas industry requirements will often call for the SCADA data to be carried on a single fiber pair while video will be carried on an other one.

Therefore some tendencies can be drawn:

- Use of mono channel transmission equipment at the network data transfer rate;
- Use of the SONET equipment as line terminal equipment sparing the need of WDM line terminal;
- Use of fiber pairs allocated to specific network data transfer.

4) Upgradability

The network upgradability is many fold. It can be through a simple line rate increase for a mono channel network from, say, OC-3 to OC-12. It can be through WDM implementation so that a fiber pair initially equipped with a single channel can be equipped with multiple channels. It can also be through equipping previously unlit fiber pair (or so-called dark fibers). Basically there is a myriad of different paths which will allow for cost effective bandwidth management within the offshore network. Different solutions can be simultaneously implemented in different parts of the network while the overall network will still transparently support and manage the new added capacity.

D) Marine Operations

1) Scope of work

It is worth mentioning the many tasks which fall under the "Marine Operations" work package. Marine Operations entail quite a lot of different activities and a broad skill range as well as a wide variety of hardware pieces (laying vessel, repair vessel, plow, remote operating vehicle, crane,...amongst others).

The following activities are most often required for a successful implementation and maintenance of a sub sea system:

- cable route study;
- burial assessment survey, route clearance;
- shore end installation, surface lay;
- main lay and burial;
- pre-lay grapnel run, post-lay activities;
- maintenance.

It is also paramount to figure out the hazards that submarine cables can face in order to ensure that the proper choices are implemented for cable protection.

External aggressions can be considered two folds: the human factors and natural factors.

Human factors are mainly commercial fishing, vessel anchors and other sea bed activities. Commercial fishing is responsible for over 75 % of cable aggression faults and most trawler related fault occur in less than 500 meter water depth.

Natural factor will be sea bed current, marine life, hostile sea bed terrain, earth quakes, underwater landslides, abrasion and they usually account for less than 10 % of cable fault.

Cable burial is the natural remedy against bottom fishing and is an all round, field proven and effective mean of protecting the cable against bottom trawling.

In stable sea bed, cable burial to over 0.75 meter is deemed sufficient against fishing aggression. Burial to as deep as 15 meters can also be carried out in extreme cases in an anchoring zone for example but it is a very expensive measure that has to be considered as a last recourse.

2) Protection schemes and philosophy

It is essential that cable breaks be kept to a minimum and therefore that the cable protection from human activities is optimized. As it has been shown, the cable protection is essentially through burial in risk areas.

But the cable design is important as well since the cable can be armored or unarmored. The cable can present a single armor layer (SA cable) or two armor layers (DA cable) as depicted in table 5.

Therefore the best protection will be offered through armoring and burial all the way through but this will yield the highest cost.

The best way forward is to analyze the cable route and define a protection philosophy striking a balance between the bundled Cable and marine Operations costs (armored cable versus not armored cable, burial versus surface laid) and the odds of the cable being hit [8].

Table 5: Lightweight (LW), Lightweight Protected (LWP), Single Armoured (SA), Double Armoured (DA)

3) Key points

In a nut shell, Marine Operations “don’t come cheap”. It will always be the cost driver for offshore type undersea networks. The reader will be well served to keep in mind a 40 to 50 % cost figure when compared to that of the whole system, again in the frame of an offshore network. It doesn’t bear a big impact whether it’s a pure telecom system, a scientific type application or an oil field communication and data transfer. The infrastructure is the cost driver and Marine Operations is the bulk of it. This will be covered in IV.

Marine Operations is also somewhat of a risky proposition in a two key areas as well: Sea conditions and permitting issues.

Difficult sea conditions may delay the cable installation which can increase the system cost a great deal since an installation vessel daily rate is in the amount of roughly 50.000 $ whether the ship can perform its duties or not.

Permits can also be a “headache” since they are necessary for laying the cable in territorial water and also at the various landing points, depending on the owner and the law in vigor. Permits often come along with a long lead time and may drive the project schedule.

E) Reliability

The network reliability is obtained through a combination of network and equipment protection. Equipment failure will affect a single piece of equipment whereas network failure will impact the link itself. Network protection guarantees proper traffic recovery whatever the failure location and bears an impact on the bandwidth requirements in the form of extra-bandwidth requirements to reroute the traffic.

The SONET and the optical layer can share the network protection burden, so that the equipment failure can be handled by the SONET layer and the optical failure can be handled by the optical layer.

Some protection mechanisms have been especially derived for submarine application in the form of self healing bi directional line switched ring. An offshore network based upon a SONET architecture and built around optical fiber should best a 99.999 % availability, so ensures less than 5 mn outage per year. The SONET and optical technology are fully secure and fully mature in this respect.

In any case, a sea route is subject to a different set of failure conditions than those of land cables. Overall statistics for terrestrial cable failures worldwide indicate for all causes there is a fault rate of 0.00062 faults/km/year [9]. In contrast, overall statistics for undersea cable failures worldwide indicate a fault rate for all causes of 0.00001 faults/km/year [10].

IV. INFRASTRUCTURE COST AND PERFORMANCE TRADE-OFFS

A) Start of Life versus End of Life system cost breakdown

Let us break down the system cost as such:

- Marine Operations
- Wet Plant (Cable and ancillary products)
- Dry Plant (Terminal equipment)
- Installation and Commissioning

A typical system price breakdown for an unrepeatered system is shown in table 6.

Life Cycle	Marine Operations	Wet Plant	Dry Plant	Installation and Commissioning
SOL	50 %	30 %	10 %	10 %
EOL	10 %	5 %	80 %	10 %

Table 6: System cost breakdown over life cycle

The EOL capacity is often 100 times that of the SOL capacity, thus explaining how the addition of dry plant equipment makes its presence felt from 10 % up to 80 %.

B) Trade-offs

1) Fiber count and fiber type

The infrastructure cost is the overwhelming factor at SOL, faring at 80 % and the cable at 30 %. Therefore it's worth taking care in selecting the fiber type and fiber count in order to minimize the cable cost.

For fiber count up to about 6 fiber pairs, the fiber cost will not make too much of a difference between the premium G.654 fiber and the standard G.652 and G.655 fiber. Moreover the G.655 fiber will display an attenuation level a fair bit in excess of that of the G.652, so the choice would lie either with the G.654 or the G.652 fibers.

For the offshore type applications (< 300 km, data rate < OC-48), the G.652 fiber will in all likelihood be the best value for money. The G.654 fiber would be advised for long haul (> 300 km) and for expected transmission up to 10 Gb/s.

The delta would be even more noticeable from 12 fiber pairs and upwards. Given the same assumptions still are true, the G.652 fiber fares much better due to the economy of scale.

The G.655 would be used in those cases when there already is a G.655 link installed and when the submarine cable is used to provide for fiber continuity.

2) Cable type and protection strategy

Even though the network traffic is protected, cable breaks should be avoided in the light of the daunting repair cost associated with it. A sum of 250,000 $ is not unusual to carry out such a repair. Also a robust and well protected cable will not require as high Operation and Maintenance costs as those of a cable system badly installed and with less sturdy cable.

Over and beyond the cable type (armored cable versus unarmored cable), burial is required in the risky areas in order to separate the cable from the man made aggression.

Depending on the soil type, the cable type to be buried could be armored or unarmored. Burying armored cable will always enhance the cable protection while burying unarmored cable could leave it exposed on the sea bed if natural de burial of the cable happens.

Burial of unarmored cable is not recommended in areas of heavy trawling, dredging, or where the seabed is not stable. Burial of unarmored cable could be recommended where a minimum burial of 0.75 m in soft but stable soil can be achieved consistently along the route. Use of unarmored cable may be recommended in areas of shallower burial if the nature of the seabed will prevent penetration of fishing equipment.

V.CONCLUSION

Unrepeatered systems are built up from commercial off the shelf technologies which have been field proven in very harsh conditions. They can readily provide undersea connectivity for all type of offshore applications.

They will also provide for unlimited bandwidth as well as built-in bandwidth flexibility. Moreover the unrepeatered systems boast the best reliability amongst other currently available technologies.

Therefore unrepeatered type system can offer a cost effective and capacity future proof solution to the full range of offshore system needs, from the telecommunication and data transfer needs to command, control and remote applications.

The oil and gas industry has already taken the leap while these systems are also gaining acceptance for application on scientific projects.

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