UNREPEATERED SYSTEMS: STATE OF THE ART

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Abstract: This paper describes the latest technology trends and industrial solutions for unrepeatered systems, focusing mainly on capacity, distance and cost. It then analyses some recent world record experiments carried out with different modulation formats and bit-rates from 10 Gb/s to 100 Gb/s up to 600 km. Transmission at 40 Gb/s is investigated over record distances reaching 500 km, then at high spectral efficiency (while comparing it to 10 Gb/s NRZ) and as an upgrade of an existing link at 10 Gb/s. Finally, a tentative perspective for future unrepeatered solutions is presented.

1 INTRODUCTION

Unrepeatered (UR) submarine systems operate without active elements under the sea and therefore provide a simple and cost-effective solution for short links. The last few years have witnessed tremendous technical evolution with the development of high power lasers for optical amplification, new modulation formats for higher bit-rates and increased capacity, and elaborate Raman amplification schemes. This paper describes the latest technologies and addresses their benefits for unrepeatered systems. Examples of record laboratory experiments demonstrate their current potential in terms of capacity and reach. Finally, further technological improvements to increase both capacity and distance are discussed.

2 KEY TECHNOLOGIES

Unrepeatered systems use a range of techniques to achieve long distances without the need for in-line repeaters. A detailed description of these is given in [1].

2.1 Modulation Formats

Like their terrestrial counterparts, unrepeatered systems traditionally apply simple modulation formats. Most demonstrations at 10 Gb/s are made with low-cost Non-Return to Zero (NRZ) modulation. At 40 Gb/s, Differential Phase Shift Keying (DPSK) is being developed and at 100 Gb/s, coherent Polarisation Division Multiplexed-Quaternary PSK is foreseen as standardized by the ITU-T.

2.2 Line Fibre

Table 1 shows different fibre types over which unrepeatered systems can be deployed. The standard line fibre is either Non-Dispersion Shifted (NDSF) or Pure Silica Core Fibre (PSCF), the latter being preferred for very long links because of its lower attenuation. Their large chromatic dispersion reduces four-wave mixing and cross-phase modulation effects in multi-channel transmission. With its large effective area, the Enhanced PSCF allows the longest reach, although it then requires more Raman pump power. By contrast, the Dispersion Shifted Fibre (DSF) and Non Zero Dispersion Shifted Fibre (NZDSF) are not well suited for repeaterless applications due to their higher loss and lower dispersion.

		CD (ps/ nm/km)	Aeff. (μm^2)	For UR
G.652	NDSF	17	80	+
G.653	DSF	0	50	--
G.654	PSCF	18.5	75	+
G.654	EPSCF	20.5	110	++
G.655	NZDSF	4 to 6	50-70	

Table 1: Fibre Characteristics and Performance

2.3 Optical Booster Amplifier

Placed at the transmitter side, optical booster amplifiers (also called post-amplifiers) improve the transmission distance by increasing the signal's launch power. Nowadays, amplifiers based on erbium-ytterbium doped fibre can yield an output power of +33 dBm. However, the channel power is limited by non-linear effects. For single channel systems, the dominating limitation is the self-phase modulation induced by the Kerr effect. For WDM systems, the limitation due to cross-phase modulation becomes predominant. When the booster power is high, the fibre introduces a power tilt between the channels [2], which has to be taken into account.

2.4 Distributed Raman Amplification

In order to extend achievable unrepeatered distances, distributed Raman post-amplification, distributed Raman pre-amplification or a combination of both can be applied.

The principle is to launch a high pump power at 1450 nm, which amplifies a signal at 1550 nm over the transmission fibre. With a pump power of 1 W at the receiver end of the system, this scheme improves the achievable distance by typically 45 km, without changing the outside plant.

Recently, significant performance improvement has been obtained with a new third-order Raman pumping scheme. It is based on the energy transfer from the primary wavelength at 1276 nm to longer-wavelength waves (1360 nm, 1450 nm and finally the signal at 1550 nm) that takes place during their propagation over the line fibre itself [3]. This improves the achievable distance by 20 km with respect to conventional pumping.

For co-propagating Raman pumping, the high-power booster at the transmitter end is replaced by a moderate-power booster amplifier from the line terminal combined with a high-power Raman pump, so that the cost impact is small. The signal power then reaches its maximum at 30 km from the transmit end of the link.

The Raman solution allows upgrading old systems installed with previous generations of terminal equipment by offering more capacity. As for new deployments, longer spans, larger capacities or higher system margins are made possible.

Over the last years, distributed Raman amplification has been deployed in numbers of telecommunication systems. We have implemented the third order pre-amplification over fibres of all types: G.652, G.653, G.654, and G.655. In all cases, we have seen a benefit over first order amplification and have not met any operational issue due to the fibre type.

2.5 Remote Optical Pre-amplifier

The remote optical pre-amplifier (ROPA) consists of a piece of erbium doped fibre (EDF) placed at about 100 km from the receiver terminal. The pump is located in the receiver terminal. As there is no electrical power feeding, this does meet the definition of an unrepeatered system. Moreover, an unrepeatered system with a remote amplifier still shows the same reliability figures as a standard unrepeatered system.

When pumped at 1480 nm, the doped fibre amplifies the signal. Powerful pump sources at 1480 nm are now readily available, and such a scheme can be easily implemented. Note that it will also benefit from the third order technique. The location of the ROPA is chosen in order to optimize the power budget and to guarantee system margins. This technique has already been deployed worldwide, and leads to the highest ultimate capacity and reach for repeaterless systems.

3 COMMERCIAL SYSTEMS

Depending on the span's length, amplifiers and Raman pumps are introduced into the system progressively in order to meet the required performance (system margin, cable ageing and repair margins) at minimal cost. The typical order of introduction of optical amplifiers is shown in Figure 1, from the shortest to the longest spans.

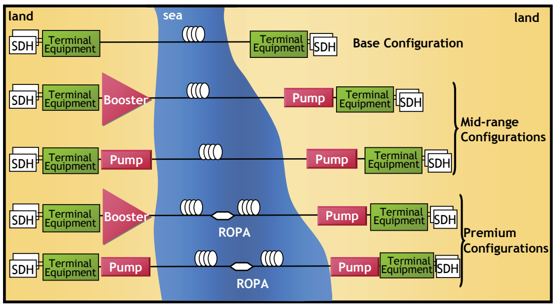

Figure 1 : Repeaterless System Configurations

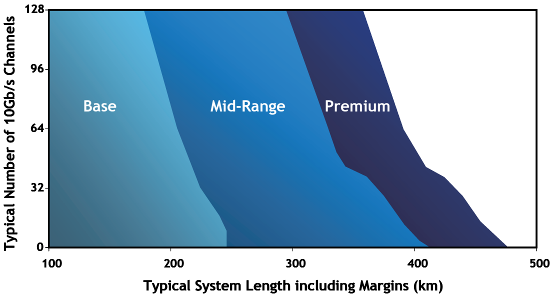

Figure 2 : Achievable System Length over G.654 at 10 Gb/s (with 3 dB Repair Margin and 10 km Land Cable)

The base configuration consists of standard line terminal equipment. For mid-range lengths, a Raman pump for distributed Raman pre-amplification is added at the receiver side, with either a high-power booster or another Raman pump for distributed post-amplification at the transmitter side. For ultimate length, a ROPA pump located in the receiver terminal activates a remote pre-amplifier; and the transmitter terminal again includes either a high-power booster or a Raman pump. Figure 2 shows the system length that can be achieved with 10 Gb/s NRZ channels over G.654 fibre, with 3 dB repair margin and including 10 km of land cable.

Whatever the configuration, reliability of a system over one fibre pair is very high and can meet 99.999 % with 4 hours MTTR, since the terminal can be equipped with high reliability line amplifiers. This corresponds to 5 mn unavailability per year.

4 LABORATORY EXPERIMENTS

This section reports several WDM unrepeatered demonstrations in the most elaborate configuration which also gives the longest reach, i.e., co-propagating distributed Raman and remotely-pumped amplification both based on third order cascaded pumping. All BERs are measured without Forward Error Correction (FEC); the FEC corrects BERs of 4x10^{-3} (Q^2 factor of 8.5 dB) to less than 10^{-12}.

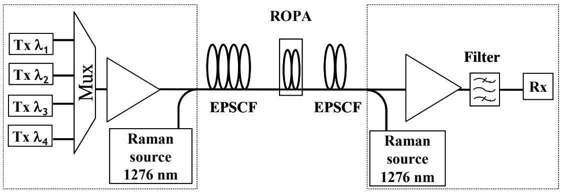

Figure 3 : Experimental Set-up for Ultra-long Distance Transmission (Configuration E)

Capacity	Length (km)	Loss (dB)	Ref
4x 10G NRZ	525	87.5	[4]
4x 10G RZ-DPSK	575	93.2	[5]
1x 10G RZ-DPSK	601	97.3	[5]
4x 40G DPSK	485	80.9	[6]
4x 40G AP RZ-DPSK	505	83.7	[7]
26x 100G PD-QPSK	401	66.9	[8]

Table 2 : Recent Laboratory Records with a Third Order ROPA Pump (All BERs are in the 10^{-3} range before FEC.)

Table 2 summarises recent laboratory experiments. These are made without industrial margins for deployment and fibre ageing, in order to show the ultimate capability of the different solutions. The longest unrepeatered distances ever reported at 10 Gb/s are 600 km for 1 channel and 574 km for 4 channels. This is achieved with an RZ-DPSK modulation format and ultra low loss fibre.

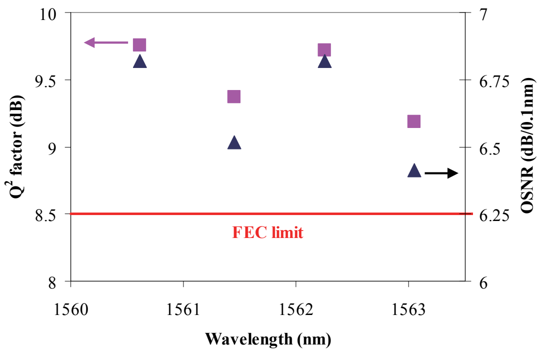

Figure 4 : Measured Q^2 Factor and OSNR after 574 km (4 Channels)

Today, 10 Gb/s UR systems are widely installed. The next generation of commercial systems will be at 40 Gb/s. The first ultra-long haul demonstration at 40 Gb/s was made over 485 km with a DPSK format. Then, the 500 km hurdle was overcome thanks to an elaborate modulation format, Alternate Polarization RZ-DPSK.

Another forward-looking example is the transmission of 26 channels at 100 Gb/s (PDM-QPSK modulation format with a coherent receiver) over 401 km. The coherent receiver enables dispersion and PMD compensation at the receiver end. The modulation format allows 50 GHz spacing (or 2 b/s/Hz spectral efficiency) and paves the way for ultra high capacity transmission, with a potential of more than 8 Tb/s over the C band only.

4.1 Comparison of 10 Gb/s and 40 Gb/s Transmission at 0.4 b/s/Hz

High efficiency transmission (0.4 b/s/Hz) over the C band can be achieved either at 10 Gb/s with 25 GHz spacing, or at 40 Gb/s with 100 GHz spacing. We therefore transmitted 6 channels at 40 Gb/s modulated with the NRZ-DPSK format, or 24 channels at 10 Gb/s NRZ over PSCF fibre, in the worst polarization conditions. The 40 Gb/s solution clearly exhibited the best performance (see Figure 5, where only the central 10 Gb/s channels are measured), the 10 Gb/s transmission being severely limited by cross-phase modulation.

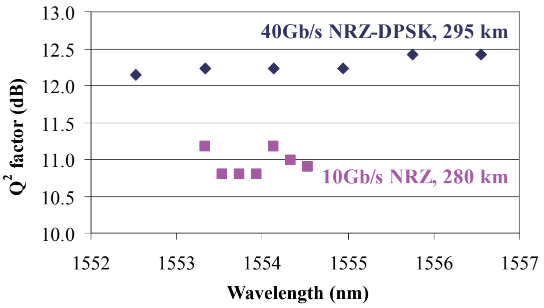

Figure 5 : Comparison of 10 Gb/s NRZ and 40 Gb/s DPSK for 0.4 b/s/Hz Transmission

4.2 System Upgrade from 10 Gb/s to 40 Gb/s

Existing 10 Gb/s links will need to be upgraded to 40 Gb/s. When upgrading a 10 Gb/s system to 40 Gb/s, additional margin must be available because of the difference in the performance of the two tributaries.

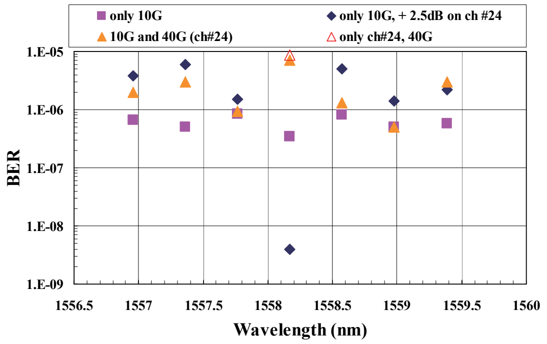

Figure 6 : Upgrading 50 GHz-spaced 10 Gb/s NRZ with 40 Gb/s P-DPSK

In our experiment with co-Raman pumping, we started with 7 channels at 10 Gb/s (50 GHz spacing), with the intention to replace the central channel at 1558.14 nm (channel #24) with a 40 Gb/s channel. The BERs of the 10 Gb/s channels were around 10^{-6}, and these channels were far from their maximum allowable power. We first increased the power of the 10 Gb/s channel at 1558.14 nm by 2.5 dB; its BER dropped to $4\ 10^{-9}$. The other 10 Gb/s channels still had a BER in the 10^{-6} range. We then replaced the 10 Gb/s card at 1558.14 nm by a 40 Gb/s card. The BER of the 40 Gb/s channel was slightly below 10^{-5}, very similar to the result without the 10 Gb/s channels. The other 10 Gb/s channels are not affected by the presence of the 40 Gb/s channel. Thus, a 10 Gb/s system with margins can easily be upgraded to 40 Gb/s.

5 FUTURE IMPROVEMENTS

What improvements can now be expected in unrepeatered systems? Both the system capacity and the length will benefit from:

- a reduction of the fibre loss from 0.170 dB/km now to 0.160 dB/km. This is the main parameter for unrepeatered performance.
- the increase of fibre effective area from 110µm^2 to typically 150µm^2. Larger effective area will require very large Raman/ROPA pump powers (7 W).
- the implementation of new FEC schemes with better correction efficiency (e.g. soft decision FEC)
- the capacity increase will be achieved by increasing the channel bit rate from 10 Gb/s to 40 Gb/s or even 100 Gb/s.

6 CONCLUSION

Unrepeatered systems can support a wide range of applications for regional communications and can be seamlessly integrated with repeatered or terrestrial solutions. Customers benefit from a cost-effective solution, since unrepeatered systems do not require submerged electronics or electrical power feeding of in-line amplifiers. Their lead time is generally shorter than that of a repeatered solution, with more flexibility at each stage of the project’s life cycle.

Taking advantage of the advent of new technologies, such as high power lasers, ultra low-loss fibre and third order Raman amplification schemes, commercial unrepeatered systems are about to reach 500 km transmission distance.

The pace of the unrepeatered R&D is not slowing either and consequently unrepeatered solutions will continue to offer a unique set of features over longer distances.

7 REFERENCES

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