UNREPEATERED SYSTEMS: STATE OF THE ART CAPABILITY

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Abstract: The unrepeatered systems technology has matured over the last three years while still providing significant improvements. The Raman amplification techniques have moved to 3rd order, more powerful amplifiers have come to the fore, new system schemes such as co- and counter-propagation have been conceived, the fiber characteristics have been improved while the terminal coding gain and modulation formats have also switched to a new generation.

This paper will review and describe the latest technology status and system schemes technologies. It will also discuss the state of the art solutions which are industrially available today or have been recently implemented. As an illustration a 380 km single-span system operating in WDM 10 Gb/s configuration, without remote optically pumped amplifiers, is detailed. Their main features will be described, focusing mainly on capacity, distance and costs.

This paper will also go over the next potential improvements in the unrepeatered arena along with a report of some world record experiments carried out. Among these records, a transmission experiment over 525 km is detailed, corresponding to the longest unrepeatered distance ever reported to our knowledge at 10 Gb/s, using commercial WDM equipment and Raman pumps ready for field deployment. A tentative roadmap will then be discussed in order to present the time frame for industrially available solutions through to 2010.

1 INTRODUCTION

Unrepeatered submarine systems have often proved their attractiveness from a cost viewpoint because they can eliminate the need for repeaters over short haul ranges.

In addition, the technical evolution in the field of unrepeatered systems has been tremendous during the last few years owing to the advent of new technologies such as high power lasers for optical amplification, new generation forward error correction, dense wavelength division multiplexing and new Raman amplification schemes.

This paper describes the above mentioned technologies and addresses the benefits of unrepeatered systems.

An example of record laboratory experiment demonstrates the current potential of such systems in terms of capacity and reach.

Finally, further technological improvements to increase both capacity and distance are discussed since they are needed to meet growing market demands.

2 UNREPEATERED SYSTEM KEY TECHNOLOGIES

Depending on their length and capacity, unrepeatered systems use techniques ranging from the very standard ones daily employed for terrestrial applications to the most advanced ones that allow to reach long distances without the need of in-line repeaters. The main technologies involved in unrepeatered systems are detailed hereafter.

2.1 Fiber

Most of the time, line fiber used in unrepeatered systems is of standard type, either non-dispersion shifted (NDSF, G.652) or pure silica core (PSCF, G.654). Usually, PSCF is preferred for very long links owing to its low loss at 1550 nm (typically 0.172 dB/km cabled against 0.194 dB/km for NDSF). Chromatic dispersions of both fibers are close (typically 18.6 ps/nm.km for PSCF and 16.7 ps/nm.km for NDSF). These large values require transmitters which can cope with a large amount of chromatic dispersion or use of compensator in the system. Note that a beneficial effect of this large chromatic dispersion is that it reduces four-wave mixing and cross-phase modulation effects in multi-channels transmission. By contrast the G.653 (DSF) and G.655 (NZDSF) fibers are not well suited for repeaterless applications due to their higher loss and lower dispersion, even if long spans are possible with adequate system design.

2.2 Wavelength Division Multiplexing

The Wavelength Division Multiplexing (WDM) technique consists in sending in the same fiber, several optical channels, each at a different wavelength and carrying its own information. Employing this technique, it is therefore possible to multiply the system capacity by the number of channels used. In practice, the maximum number of channels is limited by the available optical bandwidth of the amplifiers used in the system and by the minimum wavelength spacing between the channels. The usual bandwidth of optical amplifiers ranges from 1530 nm to 1568 nm, which means that the amplifier gain is flat over this wavelength range. In addition, the minimum spacing between two channels is actually limited by the non-linear interactions and especially cross-phase modulation in the case of dense WDM applications. The International Telecommunication Union (ITU) has defined a normalized grid to allocate the system wavelength. Using this grid, up to 96 channels can be potentially used in the C-Band with a channel spacing of 50 GHz (about 0.4 nm).

With a suitable system design, an increase in the number of channels results in only a moderate reduction of the achievable system length (see Figure 2).

2.3 Forward Error Correction

All forms of telecommunications are affected by noise and are ultimately limited by the signal-to-noise ratio. Because of the constraints of the physical transmission medium, some transmitted information can be lost or modified.

Forward Error Correction (FEC) is a method of adding some bits to a transmitted digital transmission signal, and using those bits to correct errors in the received signal. The FEC process requires 3 basics steps:

- Encoding additional bits at transmit side,
- Decoding those bits at receive side,
- Using the decoded information to correct erroneous bits in the received signal.

Thanks to FEC techniques, strong improvements in Bit Error Rate (BER) performance are available and for instance, a BER of 4×10^{-3} can be corrected into a BER of 10^{-13} using the Bose, Chaudhuri and Hocquenghem code BCH(1020,988)x BCH(1020,988) which is already industrially implemented [1]. This typically improves the terminal sensitivity by a net coding gain of 8.5dB for a BER of 10^{-13}. There are other benefits such as the use of forward error correction to improve the system margins, to improve the tolerance to polarization-dependent or non-linear effects and also to provide a quasi error-free operation for the system. Moreover the FEC allows the system operator to monitor the transmission quality. Due to equipment and fiber ageing, the bit error rate before FEC correction will increase whereas the BER after FEC will remain under the ITU limits. The fact that the number of FEC corrected errors can be monitored by software allows the operator to monitor the ageing of the system and keeps the overall system performance within the ITU limits.

2.4 Optical post- and pre-amplifier

Optical post-amplifiers bring a straightforward improvement of the distance by amplifying the signal launched into the line fiber. The use of post-amplifiers is the most obvious and attractive option to increase the achievable distance, as they directly increase the power budget without degrading the receiver sensitivity, as long as non-linear effect thresholds are not crossed.

Powerful 980 nm or 1480 nm semiconductor diodes to activate erbium-doped fiber allow to achieve output powers up to +24 dBm in a cost-effective way. Furthermore amplifiers based on erbium-ytterbium doped fiber can yield power over +33 dBm. However, the power which can be launched in the fiber is limited by non-linear effects. For single channel systems, the dominating limitation is the self phase modulation induced by Kerr effect. In this case, the maximum launch power over standard fiber is typically +18 dBm for NRZ modulation format but larger powers can be launched by using a combination of fibers in the line [2]. For WDM systems, the limitation due to cross-phase modulation becomes predominant and the power per channel has to be reduced.

Optical pre-amplifiers are introduced into the systems to improve the terminal sensitivity by masking the electronics receiver thermal noise. Their design requires an optimization different from that of the post-amplifier one, the most important feature being the noise figure whose reduction leads to better system performances. The best noise figures are obtained with 980 nm pumping and can be as low as 3.5 dB, whereas 5 dB is usually obtained with 1480 nm pumping.

The optical pre-amplifier has to be combined with a narrow filter in order to filter the large noise spectrum generated by the amplifier. The optimization of the filter bandwidth has to take into account the transmitter linewidth and the non-linear effects which can broaden the signal spectrum. Filters in the range 0.2 nm to 0.5 nm are typically used.

2.5 Distributed Raman amplification

In order to extend achievable distances with local optical amplifiers, a further scheme consists in using distributed Raman post-amplification, distributed Raman pre-amplification or a combination of both.

The principle is to launch a large pump power at around 1450 nm into the line fiber. Thanks to Stokes wave generation in the Silica, amplification is provided to the signals around 1550 nm. By using a pump power of 1 W at the receive end of the system, this scheme improves the achievable distance by typically 45 km (or allows to increase the system capacity by a factor of 6), without changing the outside plant. Very large power pump sources used for this application are themselves based on Raman effect internally and are therefore called Raman pumps.

The Raman pre-amplification technique has been used for years in deployed systems with very good results. Nonetheless, new Raman amplification scheme came to the fore recently, based on third-order pumping and allowing significant performance improvement. The third-order cascaded pumping repartition is driven by the energy transfer from the 1276 nm primary wavelength to longer-wavelength low-power waves that take place during their propagation along the fiber [3]. In conventional Raman systems, the 1276 nm to 1450 nm conversion takes place inside the Raman pump, whereas it happens within the line fiber itself in the case of third order pumping. As a consequence, the 1450 nm pumping power reaches its maximum value about 20 km away from the receive end of the link allowing to improve the achievable distance by 20 km with respect to conventional pumping.

When co-propagative Raman pumping is used, the usual high-power booster of the transmit terminal is replaced by a moderate-power booster amplifier combined with a high-power Raman pump, so that the cost impact is very small.

Using a co-propagative third order pumping scheme, the traffic signal power reaches its maximum about 30 km away from the transmit end of the link resulting in a better power distribution at the transmit side.

This solution allows to upgrade old systems using previous generation of terminal equipment by offering more capacity. As far as new deployments are concerned, longer spans, larger capacities or higher system margins are made possible.

One can note that third order pumping improves the system performance fairly significantly when compared to conventional first order pumping. Now it is worth bearing in mind that higher order schemes (4^{th}, 5^{th}, 6^{th}…) will likely not provide an improvement high enough to bring an industrial benefit [4].

In the last decade, distributed Raman pre-amplification has been deployed in numbers of telecommunication systems and coincides with the availability of high power pumps. Distributed Raman post-amplifiers have been implemented more recently in systems, because high power booster were already available and benefit in terms of performance is lower at transmit side than at receive side.

2.6 Remote optical pre-amplifier

The remote optical pre-amplifier (ROPA) consists of a piece of erbium doped fiber located about 100 km away from the terminal. The doped fiber amplifies the signal owing to the pump power which is sent from the receive terminal. As there is no electrical power feeding, this system does meet the definition of unrepeatered systems. Such a scheme can be practically implemented owing to the availability of very powerful 1480 nm pump sources (conventional pumping) and will also benefit from third order technique [5]. The location of the ROPA is chosen in order to optimize the power budget and to guarantee system margins.

This technique has been already deployed worldwide and leads to ultimate capacity and reach of repeaterless systems.

3 UNREPEATERED SYSTEM ACHIEVABLE SPAN

3.1 Commercial systems

Depending on span at stake, amplifiers and Raman pumps are introduced into the system in a progressive manner which strikes the best balance between the overall solution performances and costs. The typical order of introduction of optical amplifiers is shown in Figure 1, from the shortest to the longest distance.

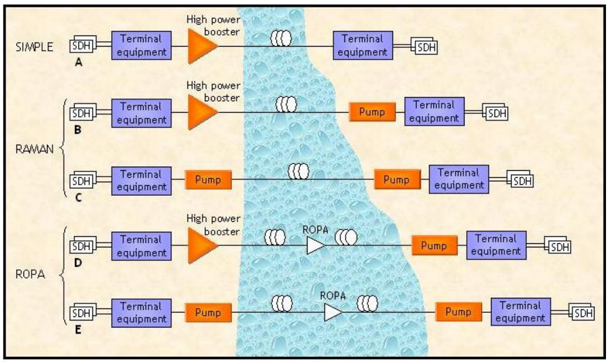

Figure 1: Optical amplification configurations

Configuration A uses the line terminal equipment plus an optical post-amplifier at transmitter side.

Configuration B uses a Raman pump to perform distributed Raman pre-amplification.

In Configuration C, the booster is replaced by a Raman pump for distributed post-amplification.

Configuration D uses a Raman pump to activate a remote amplifier located more than 100 km away from the receive terminal.

In Configuration E, both Raman post-amplification and remote pre-amplification are used.

One can note that whatever the system configuration, reliability of the one fiber pair system is very high and can meet 99.999 % with 4 hours MTTR, since the terminal can be equipped with high reliability line amplifiers. This roughly meets the 5 mn unavailability per year.

The Figure 2 below shows the typical achievable spans using these configurations over G.654 fiber.

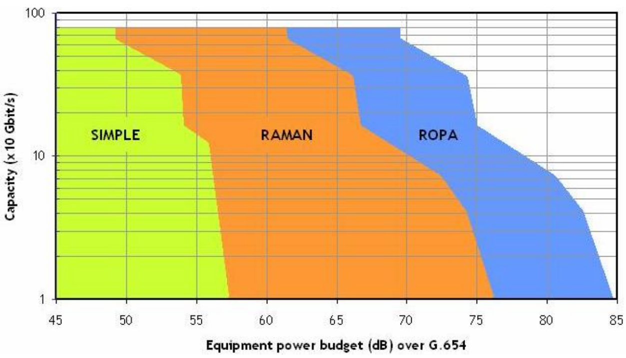

Figure 2: Attainable spans at N x 10 Gb/s over G.654

As a practical example, a WDM transmission system has been recently deployed, capable of carrying four channels at 10 Gb/s over 380 km of PSCF without the use of ROPA. Referring to Figure 1, the system configuration is of type B and the end-of-life cable loss is 70 dB at 1550 nm. To reduce the impact of non-linear effects, channels have been allocated on a 200 GHz ITU grid, from 1552.5 to 1557.4 nm. As a result of this design optimization, the system operates error-free for all channels after the margin have been taken into account (cable ageing and repair margins).

3.2 Laboratory experiments

A straight forward solution to increase the achievable distance is to introduce a remotely pumped amplifier in the line. Several schemes are possible to improve the efficiency of the ROPA, for example dedicated pumping fibers, in-line Raman noise filtering or ultra-large effective area fibers but their use would be challenging from a practical standpoint, notwithstanding the Non Recurring Expenses required to develop such solutions.

This paper reports the first WDM unrepeatered demonstration using co-propagating distributed Raman and remotely-pumped amplification both based on third order cascaded pumping. To the best of the authors's knowledge, the 525 km distance achieved represents the longest unrepeatered distance ever reported at 10 Gb/s. In addition, this system is based on WDM commercial equipment and does not require any dedicated fiber to activate the ROPA.

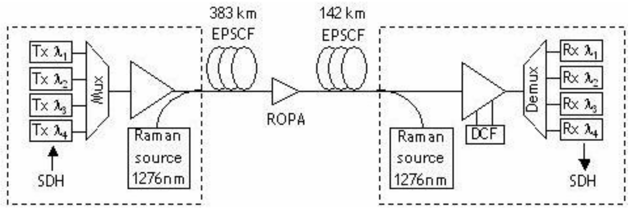

Figure 3: Experimental set-up for 525 km transmission

Figure 3 shows the system configuration where advanced co-propagating Raman amplification and remotely-pumped amplification are both based on third-order cascaded pumping scheme. In this experiment, all channels are transmitted error free over 525 km of 110 μm^2 pure silica core fiber, yielding a total loss of 87.5 dB at 1556 nm. Here, the front end net benefit of Raman co-propagating pumping with respect to conventional booster configuration is a 3 dB Q-factor improvement. At the back end , the efficiency of third-order ROPA pumping is so high that it has simply lead to the farthest ROPA location ever reported for a 10 Gb/s WDM unrepeatered system.

4 FUTURE IMPROVEMENTS

In the near future, unrepeatered systems will continue to take advantage of research and innovation in the domain of optical transmission. Both the system capacity and the system length will potentially be further increased owing to:

- a reduction of the fiber loss from 0.170 dB/km now to 0.155-0.160 dB/km through improvement of design and manufacturing process,
- the increase of fiber effective area from 110µm^2, currently deployed, to 200µm^2 as already demonstrated in the laboratory,
- the use of new modulation formats (RZ, RZ-DPSK,…), instead of standard NRZ, for a better resistance to noise and non-linear effects,
- the implementation of new FEC schemes with better correction efficiency (soft decision, …),
- the increase of channel count from 96 now to 192 by extending the conventional C-band (1530-1568 nm)

to longer wavelength range in the L-band (1570-1620 nm),

- the increase of the channel bit rate from 10 Gb/s to 40 Gb/s which may be the standard bit rate in the next few years,

- the use of new devices for chromatic dispersion compensation (Bragg, tunable device…).

It is not an easy task to foresee the commercial availability of these different pieces of technology so that span improvements are also difficult to predict. Nonetheless, the roadmap displayed in Figure 4 aims at providing the best case scenario where the 550 km mark could be attainable in 2009-2010. This is obviously a technological stance which does not take the cost aspects into account.

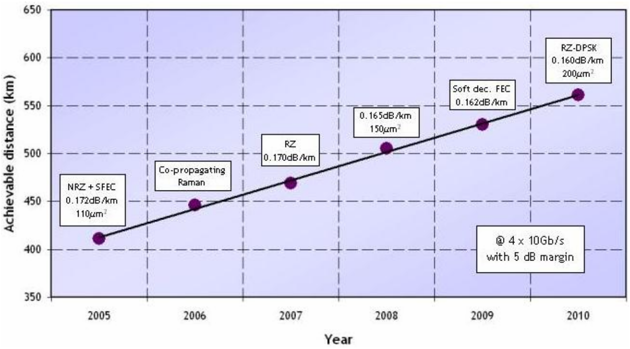

Figure 4: Unrepeatered systems roadmap

5 CONCLUSION

Taking advantage of the advent of new technologies, such as high power lasers, forward error correction and third order Raman amplification schemes, unrepeatered systems are poised to support 500 km solutions in the near future.

They can support a wide range of applications for regional communications and can also be seamlessly integrated with repeatered or terrestrial solutions.

Customers will benefit from a cost-effective solution since unrepeatered systems do not call for submerged electronics nor electrical power feeding of in-line amplifiers. The lead time of unrepeatered solution is generally shorter than that of repeatered solution with more flexibility at each stage of the project's life cycle.

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

6 REFERENCES

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