THE RZ-DPSK MODULATION FORMAT IN LONG-HAUL TRANSMISSION SYSTEMS

Alexei Pilipetskii, Morten Nissov, and Neal S. Bergano

apilipetskii@tycotelecom.com

Tyco Telecommunications, 250 Industrial Way West, Eatontown, NJ 07724, USA

Abstract: An effective way to enhance the transmission capabilities and reduce the first cost of long-haul WDM systems is to improve the terminal's performance. One promising modulation format for long-haul operation is the Return-to-Zero, Differential Phase Shift Keyed (RZ-DPSK) modulation format. The allure of RZ-DPSK is that it provides a combination of 3 dB improvement in OSNR sensitivity due to balanced detection and benefits of RZ pulse shapes. An important issue with 10 Gb/s DPSK transmission is whether the 3-dB benefit over On-Off Keyed (OOK) exist for long-haul transmission over transoceanic distances that are limited by fiber nonlinearities.

1. INTRODUCTION

A fundamental design challenge for undersea data transmission is the very long distances that optical signals have to travel (in some cases more than 10,000 km) without regeneration. Large transmission distances require many optical amplifiers which can lead to increased amplified spontaneous emission (ASE) noise and therefore lower optical signal to noise ratio (OSNR) [1]. To ensure adequate OSNR at the receiver the signal must be transmitted with high optical power; however, the combination of increased signal power and long distance can cause nonlinear distortions [1]. To satisfy these engineering tradeoffs a host of advanced transmission technologies have been used in long-haul systems, such as the nonlinearly tolerant chirped return-to-zero on-off keyed (CRZ-OOK) modulation format [1-4], advanced forward error correction (FEC) techniques [5-7], and advanced fiber designs. [2,3,8,9] The use of these advanced technologies enabled the deployment of 10 Gb/s per channel transoceanic systems with total capacities of about 1 Tb/s per fiber [10].

The down-turn of the telecommunication market caused a paradigm shift toward reduced "first cost". One way to reduce first cost is to increase the distance between repeaters by using terminals with improved performance made possible by advanced FECs [11, 12] and modulation formats. One promising modulation format for long-haul operation is the Return-to-Zero, Differential Phase Shift Keyed (RZ-DPSK) modulation format [13, 14]. Over the past few years a significant amount of R&D effort has been focused on the DPSK modulation format [16-22]. After performing comprehensive studies using computer simulations and transmission experiments we conclude that the RZ-DPSK format is an excellent choice for the next generation of terminals for long-haul undersea cable systems.

2 TRANSMISSION PROPERTIES OF 10 GB/S RZ-DPSK MODULATION FORMAT

Initially, an important issue with 10 Gb/s DPSK transmission was whether or not the 3 dB balanced benefit existed for long-haul, nonlinear transmission [23, 24]. To address this issue we designed new computer models for DPSK transmission and performed several experiments on both an installed system [17,20] and laboratory testbeds [16,18]. First, we successfully demonstrated that 10 GB/s RZ-DPSK channels could propagate on existing systems using a Trans-Atlantic segment of TGN (TATA Global Network). In one experiment, 96 channels with 33 GHz spacing were transmitted over 13,000 km, where the signals crossed the Atlantic ocean twice, where the maximum amount of accumulated dispersion was about 13,000 ps/nm/km [17]. In a second experiment on TGNA [20] the performance of RZ-OOK and RZ-DPSK were compared after propagation of 128 channels with 25 GHz channel spacing through a single 6,550 km pass of the cable. These experiments demonstrated that the RZ-DPSK transmission format could perform well over long, nonlinear segments, even in the presence of large accumulated amounts of chromatic dispersion. Later test bed experiments confirmed these results by showing a large immunity to noise, nonlinearity and large dispersion accumulation [18].

The transmission performance of RZ-OOK and RZ-DPSK @ 33 GHz channel spacing was also studied numerically for the case of a typical transpacific transmission distance of 8,500 km. The result is shown in Fig. 1. The 26 nm system modeled in [21] had a conventional dispersion map with the zero dispersion wavelength in the middle of the band and a realistic system gain shape. The computer modeling showed that the performance characteristics of the two modulation formats are very different. For small accumulated dispersion the 10 Gb/s RZ-OOK modulation format experiences less nonlinear penalties than RZ-DPSK, which suffers from nonlinear noise and WDM channel crosstalk [22]. However, even under such conditions RZ-DPSK has superior performance up to very long transpacific distances [21]. For very large accumulated dispersion in the so called "pulse overlapped regime" the RZ-DPSK format give far superior performance; demonstrating the robustness of phase encoded relative to amplitude encoded signals [20,21]. As a result RZ-DPSK signals can have even more than 3 dB performance advantage over RZ-OOK channels for the same power per channel and transmission distance for properly designed dispersion maps. This superior DPSK performance can be qualitatively explained by an effective suppression of intra-channel four-wave mixing due to an absence of strong spectral components at carrier and side-band frequencies. A general conclusion can be made that phase encoded signals are more suitable for transmission in a highly dispersive bit overlapped regime than amplitude encoded signals. As a result RZ-DPSK modulation format gives significant flexibility in the design of the dispersion path and is an excellent choice for the next generation of long-haul undersea cable systems.

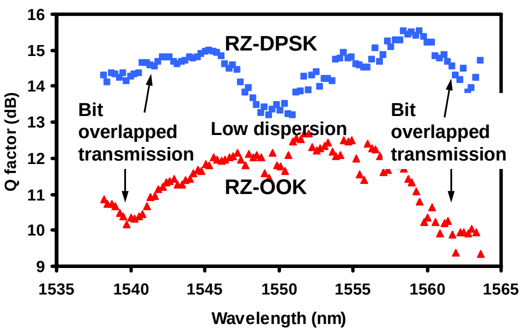

Fig. 1. Comparison of RZ-DPSK and RZ-OOK performance (simulation) in conventional dispersion map after 8500 km transmission [21].

3 SYSTEM DESIGN BENEFITS OF 10 GB/S RZ-DPSK TERMINALS

The benefits of 10 Gb/s RZ-DPSK terminals are the increase in available system margin due to the 3 dB balanced receiver benefit, and superior propagation performance; both of which aid the system design. The added margin can give a significant reduction in wet plant costs by stretching repeater spacing. Moreover 10 Gb/s RZ-DPSK significantly expands transmission distances of dense WDM systems well beyond 12,000 km with sufficient performance margin. To illustrate this point one can compare the results of the transmission experiments using RZ-OOK [10] and RZ-DPZK [25] modulation formats over dispersion flattened fiber (DFF). Both experiments used the same 33 GHz channel spacing and the dispersion maps were optimized for the respective modulation format [10, 25]. The DFF spans were constructed from large effective area ~100 μm^2 fiber with positive dispersion of 20 ps/nm/km followed by negative dispersion fiber of -40 ps/nm/km with effective area of ~30 μm^2. In the case of RZ-OOK an average Q-factor of 12.5 dB was achieved after transmission over 9,000 km through a chain of amplifiers with 45 km spacing. For the case of RZ-DPSK an average Q factor of 12 dB was achieved after transmission over 12,700 km with 75 km amplifier spacing (fig. 2). The improvement in receiver sensitivity allowed the substantial increase in both repeater spacing and distance.

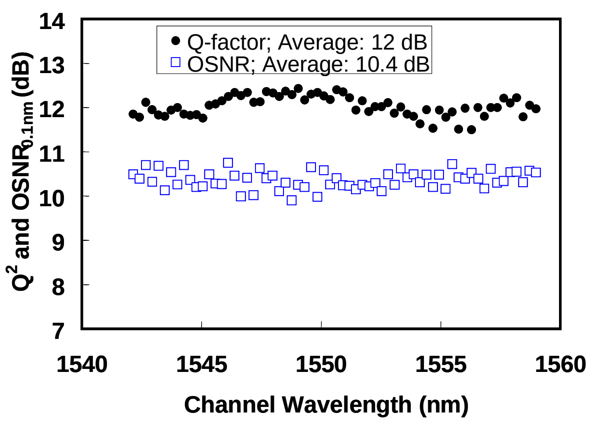

Fig. 2. Q-factor and OSNR of RZ-DPSK modulation format after transmission over 12,700 km with large amplifier spacing 75 km [25].

Further repeater spacing benefits may come from more complicated amplification schemes such as Raman assisted EDF amplification. The RZ-DPSK modulation format is the best choice for such systems since the potential gain in OSNR is larger when Raman amplification is added to the longer spans. Transmission over transpacific distances with an amplifier spacing of 150 km was demonstrated experimentally in [26, 27]. The Experiment described in [27] used DFF spans with backward Raman pump injected in negative dispersion fiber. The Dispersion map, Raman gain, and EDFA output power were optimized for RZ-DPSK transmission of 93 channels on 33 GHz grid over a distance of 8900 km resulting in an average Q-factor of 11.2 dB.

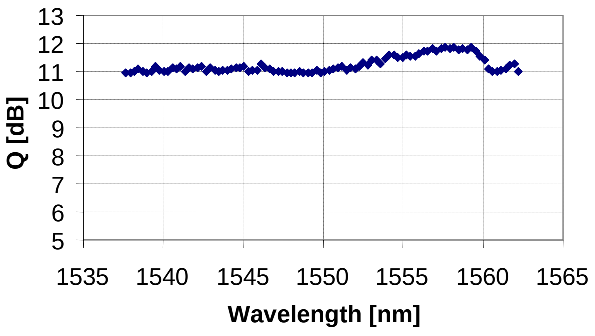

Fig. 3. Performance of RZ-DPSK modulation format after transmission over 8,900 km in Raman assisted EDFA chain with amplifier spacing 150 km [27].

The upgrade market will also benefit from 10 Gb/s RZ-DPSK terminals; these modern terminals might allow ultimate system capacities beyond what was possible using the OOK modulation format. As can be seen from experimental demonstrations and numerical studies [17, 20, 21] transmission of RZ-DPSK channels can be done with superior performance on presently installed undersea cables. The major advantage of the RZ-DPSK modulation format in an upgrade environment is that it allows the most efficient use of available repeater power. In a linear system the 3 dB receiver sensitivity improvement can translate into a doubling of the capacity of a system when OOK channels are replaced with RZ-DPSK channels (provided that there is enough transmission bandwidth in the amplifiers to do so). In some cases a reduction in nonlinear penalties can be obtained through the reduction of power per RZ-DPSK channel. In most of the cases RZ-DPSK makes it possible to divide the available repeater power between larger numbers of RZ-DPSK channels than was possible with previous generations of terminal equipment; thus, improving ultimate system capacity. This point can be illustrated by results from experiments using a test-bed with a design representative of the first generation of 2.5 Gb/s WDM systems [28]. Transmission of five 2.5 Gb/s OOK, seventeen 10 Gb/s RZ-DPSK and one 10 Gb/s RZ-OOK channel was done over a 2500 km test-bed, which used 1480 nm pumped EDFAs with 83 km spacing. It can be seen from Figure 4 that upgrading a 2.5 Gb/s system to 10 Gb/s RZ-DPSK can significantly increase system capacity beyond its original design. In contrast 10 Gb/s RZ-OOK channels cannot provide similar ultimate system capacity with adequate performance.

The RZ-DPSK modulation format may also make 40 Gb/s transoceanic transmission possible. The RZ-DPSK modulation format with its 3 dB receiver sensitivity advantage and its high robustness to nonlinearity in the 'pulse overlapped' transmission regime might be one of the enabling technologies that will allow 40 Gb/s systems to reach transoceanic distances [22, 29]. Although, to make 40 Gb/s transmission practical, the performance gap between 40 Gb/s and 10 Gb/s transmission needs to be bridged to provide cost efficient system design solutions.

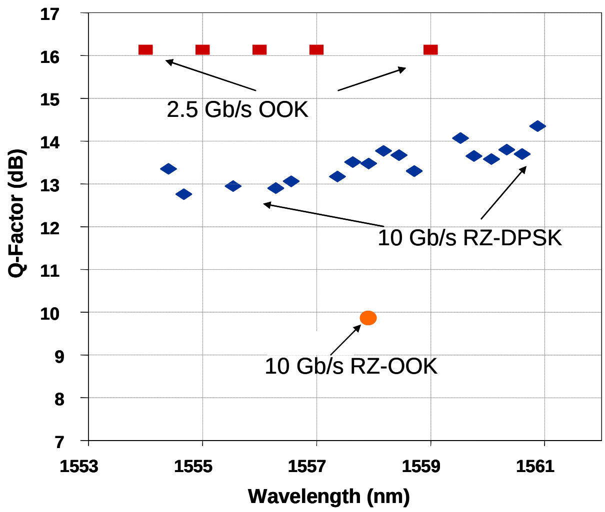

Fig. 4 Performance of five 2.5 Gb/s OOK, seventeen 10 Gb/s RZ-DPSK and one 10 Gb/s RZ-OOK channels in the transmission experiment using legacy test-bed [28].

4 CONCLUSIONS

10 Gb/s RZ-DPSK terminals represent a significant advancement in modern long-haul undersea transmission technology. The application of the 10 Gb/s RZ-DPSK modulation format makes it possible to build new high capacity cost efficient undersea cables and to give an efficient upgrade path for existing systems.

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