40 GB/S TRANSMISSION IN LONG-HAUL UNDERSEA NETWORKS

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Abstract: Enabling technologies for future 40G systems are described: dispersion slope compensation, polarization mode dispersion compensation, choice of modulation formats, and forward error correction. These technologies will be needed for future applications of 40G in long haul undersea networks. The upgradeability of previous and present generations of systems is then discussed.

1 INTRODUCTION

Terrestrial operators have started to rollout 40G technology in the terrestrial backbone network. The potential reductions in terminal costs and the ease of managing only a quarter of the wavelengths make 40G technology attractive. Typically, the 10G transmission technology used in terrestrial systems is less advanced than that used in undersea systems. Thus, when terrestrial network planners make the 10/40G comparison, they may find transmission benefits from making the switch to 40G. This 10/40G comparison is somewhat different for undersea systems where the transmission distances are more challenging and advanced 10G terminal technology is already in use. In submarine cable systems where the terminals and wet transmission paths are highly optimized to provide customers with the best 10G value proposition, a 40G terminal advantage might not exist. Thus, a trade-off in capacity or repeater spacing might be required for "40G ready" systems. Undersea use of 40G technology is therefore only likely to happen when significant traffic is carried from 40G router cards through terrestrial networks into the undersea cable station, and when a strong desire exists that capacity be transported undersea as 40G channels.

The undersea market for 40G is likely to consist of system upgrades and new systems optimized for both 10G and 40G without sacrificing repeater spacing. For both types of systems new 40G technologies are needed that have an inherent advantage over those used for 10G so as not to increase the wet plant cost over that necessary for 10G.

2 40G ENABLING TECHNOLOGIES (PRESENT & FUTURE)

The following discussion will present technologies that might be needed for competitive 40G solutions. Some of the technologies, such as dispersion slope compensation and polarization mode dispersion (PMD) compensation, are only needed for binary transmission rates exceeding 10G. Others, such as better modulation formats and forward error correction (FEC), might also be of benefit for 10G transmission.

2.1 Dispersion slope compensation

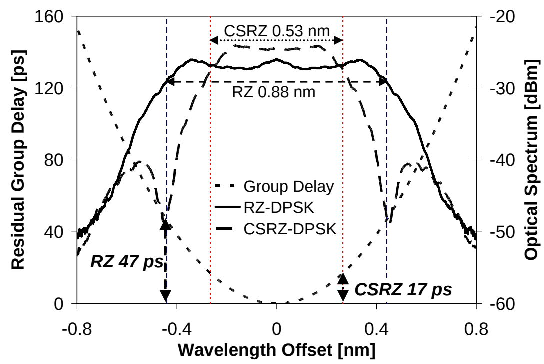

Figure 1: Residual group delay (after dispersion compensation) after 6,250 km, and optical spectra for RZ-DPSK and CSRZ-DPSK [1].

An optical signal's sensitivity to dispersion and dispersion slope is determined by the spectral width of the optical signal. This sensitivity scales by the square of the bit rate (for dispersion) and the cube of the bit rate (for dispersion slope). Thus, binary 40G is 16 times more sensitive to dispersion and 64 times more sensitive to dispersion slope than binary 10G. Intra-channel dispersion slope (i.e., the dispersion slope within the spectral bandwidth of the signal) has virtually no impact for 10G transmission, but can cause substantial penalties for 40G binary transmission [1-2]. The transmission penalty associated with dispersion slope is greatly reduced when the newer dispersion flattened fiber sets are used. However, the dispersion slope of conventional submarine fibers used in most deployed systems is sufficiently large to cause 40G penalties for most transoceanic system lengths if left uncompensated. Figure 1 illustrates that 40G modulation formats with narrower optical spectrum will experience less group delay variation across the signal's bandwidth and thus suffers less from uncompensated dispersion slope. This signal bandwidth difference is why 40G CSRZ-DPSK is less sensitive than 40G RZ-DPSK.

Figure 2a shows the transmission performance after 9,020 km using conventional undersea fiber as a function of dispersion slope compensation ratio. A slope compensation ratio of 0% corresponds to no dispersion slope compensation, and similarly a ratio of 100% corresponds to full dispersion slope compensation. The data in this figure shows that even dispersion tolerant 40G modulation formats (such as CSRZ-DPSK) can experience a penalty of 2 dB without compensation. With RZ-DPSK and full slope compensation performance improves by more than 3 dB over the case without slope compensation. The eye diagrams shown in Figure 2b also illustrate this point that the best performance is achieved with full slope compensation. In this set of measurements the dispersion slope was compensated using simple per channel slope compensators at the receiver.

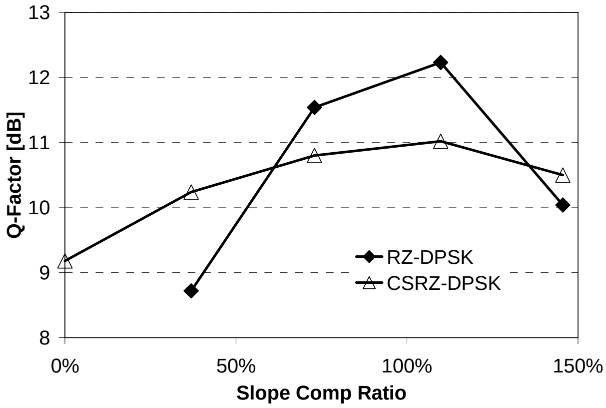

Figure 2a: Q-factor vs. slope compensation ratio after 9,020 km [1].

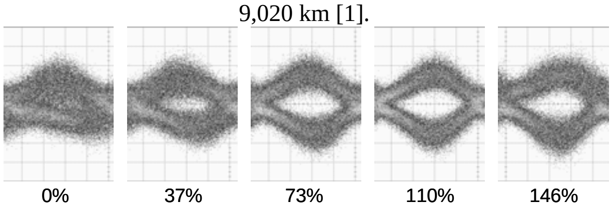

Figure 2b: Balanced eye diagrams for the RZ-DPSK formatwith different slope compensation ratios. [1]

2.2 PMD compensation/low PMD fiber

Polarization induced fluctuations are a major issue for long distance transmission at rates above 10G. The polarization induced fluctuations are caused by polarization dependent loss (PDL) of the repeaters and polarization mode dispersion (PMD) in the optical fiber and the components of the repeaters. The PDL driven fluctuations are present at any bit rate; however, the PMD driven fluctuations scales with bit rate. From a system design point of view it is important to minimize the performance fluctuations caused by PMD. A rough estimate can be made based on first order PMD only. It indicates that a system PMD of ≤ 0.02 ps/km$^{1/2}$ is needed to limit the PMD driven fluctuations. This system effective PMD level includes PMD from both the optical components and the transmission fiber. Such a low PMD specification might be hard to achieve and would likely reduce yields both in fiber and component manufacture. It is therefore likely that systems designed and deployed for 10G operation will not satisfy this stringent PMD specification. For shorter systems the inevitable PMD fluctuations might be absorbed in the impairment budget, in the form of a larger Q-factor fluctuation allotment. For example, ~2.5 dB of “fluctuation margin” might be needed for a system of 3,500 km with 0.06 ps/km$^{1/2}$ of PMD. For longer systems the PMD must either be compensated for (i.e., using a PMD compensator) or a lower symbol rate is needed (i.e., through the use of higher order modulation formats).

PMD compensation can be performed using combinations of controllable endless polarization controllers (typical electro-optical) and variable linear birefringence devices. Both single- and dual-stage PMD compensation has been investigated. Feedback signals are often based on degree-of-polarization (measured by a polarimeter) or detected microwave signals. PMD compensation can to a large extent alleviate the issues related to PMD at the expense of extra channel specific equipment [3]. Due to different polarization histories each channel must have its own compensator.

2.3 Modulation formats

The choice of modulation format can have a strong impact on transmission performance. For low data rate signals (<<10G) the main figure-of-merit is receiver sensitivity. At 10G nonlinear propagation tolerance is traded off with receiver sensitivity. A good choice for 10G propagation is the RZ-DPSK [4-9] modulation format. For higher data rate binary transmission, the choice of modulation format represents not only a trade-off between receiver sensitivity and nonlinear tolerance, but also PMD tolerance (unless PMD compensation is used). This is illustrated in Figure 3 [10]. The figure shows the probability density functions of Q-factor for several different modulation formats after 6,550 km measured in the laboratory. The highest median Q-factors are achieved by the binary modulation formats: RZ-DBPSK and APRZ-DBPSK [11-12]. However, those formats (in particular the APRZ-DBPSK format) suffer from larger fluctuations. The quaternary RZ-DQPSK [13-16] modulation formats on the other hand had lower medium performance (due to incoherent detection penalty), but also much lower fluctuations. This is mainly due to the narrower spectral shape of the 20 GS/s modulation formats, which make them less susceptible to PMD [10]. This data indicates that a PMD-compensated binary modulation format might give the best engineering trade-off.

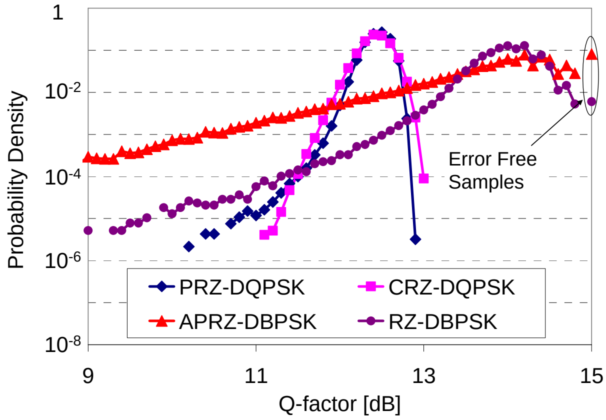

Figure 3: Long term Q-factor distributions for 4 modulation formats. [10]

Recent work has also looked into even more advanced modulation formats, in particular coherent modulation formats. Those studies have looked into variants of BPSK and QPSK [17-18]. There has also been work performed on optical orthogonal frequency division multiplexing (OFDM) [19]. It is still too early to say whether any of those formats will add needed performance to undersea applications of 40G.

2.4 Forward error correction

Improved FEC can provide benefits both at 10G and 40G. Many systems installed around year 2000 were designed with the first and second generations of FEC (labeled "previous" in Table 1). Present generations of FEC improves performance at 20% by 1.4 dB. Of significance to 40G upgrades, this newer generation of codes gives a performance benefit at 7% overhead similar to previous FECs working at 20% overhead. This is important since 40G transponders are likely to use lower overhead codes, because of the difficulty in building high-speed opto-electronic devices. Terrestrial suppliers are likely to stay with 7% overhead which reduces the impetus of FEC manufacturers to develop higher overhead FECs. The optimal 40G FEC overhead for undersea system is likely to be in the range of 10-20%. For upgrades of modern systems utilizing the present generation of FEC, 40G would likely have to use similar strength FEC. Staying at 7% overhead would probably not be enough, since the performance of the present generation FEC with 20% overhead (9.9 dB) cannot be matched at 7% even with the best published FEC (labeled soft TPC).

Looking forward even better FECs are possible. The 4th row in the table provides data for the best published FEC 3-bit soft decision Turbo product code [20]. Notice, however, that the performance improvement at 7% overhead is only 0.3 dB. At larger overhead up to 1 dB can be gained at the expense of a more complex receiver. This FEC is already getting very close to the fundamental limit (by 1.7 dB) and FEC can therefore not be relied upon to substantially close remaining gaps between 10G and 40G. Furthermore, any advances in FEC are likely to have more significant impact at 10G where larger overhead can be used.

FEC	Net effective coding gain for 1E-15 BER	
	7%	20%
Previous generation	6.2	8.5
Present generation	8.5	9.9
Soft TPC	8.8	10.9
Shannon limit	11.2	12.6

Table 1: Comparison of FECs

3 SYSTEM APPLICATIONS

Systems designed for the previous generation of terminal equipment (e.g., CRZ-OOK) are typically characterized by ~50 km repeater spacing [21]. Thus, using a modern modulation format such as RZ-DPSK for the 40G channels together with a modern FEC the entire gap between 10G and 40G can be bridged for many systems lengths. Figure 4 shows the result of an experimental study at 6,500 km where the performance of 40G RZ-DPSK channels is compared to that of 10G RZ-OOK channels. All measurements were performed with equivalent 10G capacity of 72 channels using 18 nm of bandwidth. This figure demonstrates that such systems can be upgraded to 40G using modern modulation formats and FECs. Since most of these systems were built using conventional undersea fiber both dispersion slope and PMD compensation would be needed on a per channel basis.

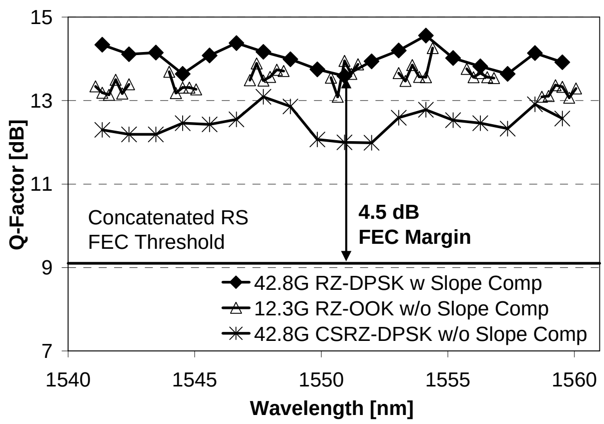

Figure 4: Q-factors for 42.8 Gb/s RZ-DPSK (w/ slope compensation), 42.8 Gb/s CSRZ-DPSK (w/o slope comp.), and 12.3 Gb/s RZ-OOK [1].

The upgrade path to 40G might be more challenging for modern 10G systems built with today's technology. Systems designed for the present generation of terminal equipment (RZ-DPSK) are typically characterized by longer repeater spacing [22]. Compared to such 10G terminals 40G terminals are unlikely to have a distinct advantage in terms of modulation format or FEC. Furthermore, 40G terminals employing 7% overhead

FEC are at a disadvantage. 40G terminals used to upgrade such new systems are therefore likely to be based on higher overhead FECs. Also, since 40G generally does not propagate as well as 10G (unless very linear fiber is used) more advanced modulation formats are needed that are either less sensitive to nonlinearities, or provide better receiver sensitivity. Some of the recent modulation formats studied was listed previously.

4 CONCLUSION

Enabling technologies for 40G transmission has been described: dispersion slope compensation, PMD compensation, FEC, and modulation formats. Dispersion slope compensation is necessary to enable 40G propagation over conventional undersea fibers. PMD compensation allows the stringent requirements on component and fiber PMD to be avoided.

Most of the older generation of systems designed for 10G RZ-OOK should be upgradeable to 40G using present techniques, including: RZ-DPSK modulation format, strong FEC, dispersion slope compensation, and PMD compensation. Recent systems designed for modern 10G technology are more challenging to upgrade. Dispersion slope and PMD compensation might still be needed. In addition even stronger FEC and more nonlinearly tolerant modulation formats are needed.

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