Single- versus Dual-Carrier Transmission for Installed Submarine Cable Upgrades

Lutz Molle, Markus Nölle, Colja Schubert (Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut), Wai Wong, Steve Webb, Jörg Schwartz (Xtera Communications)
Email: Lutz.Molle@hhi.fraunhofer.de

Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut,
Einsteinufer 37, D-10587, Berlin, Germany

Xtera Communications, Bates House, Church Road, Harold Wood, Romford RM3 0SD, United Kingdom

Abstract: This paper discusses the viability of different modulation and transmission technologies for upgrades of legacy submarine cables. We report on results of a coherent 100-Gb/s field trial over 2nd generation submarine cables, where we compared the transmission performance of a single-carrier and a dual-carrier approach over distances up to 5800 km. The tests included dual-polarization quadrature phase shift keying (DP-QPSK) as a single-carrier format, as well as a dual-carrier (DC) solution which uses dual-polarization binary phase shift keying (DP-BPSK). The single-carrier DP-QPSK transmission showed a much lower Q-margin relative to the soft-decision (SD) FEC threshold. However, due to the reduced spectral efficiency of BPSK compared to QPSK, the dual-carrier approach requires a higher channel bandwidth, even when employing baud-rate spacing of the two subcarriers.

1. INTRODUCTION

The extensive growth of the internet traffic due to new bandwidth demanding applications and services leads to increased demand for high capacity optical backbone infrastructure. There are in principle two ways to deal with this capacity demand: an upgrade of the legacy fibre infrastructure or a new-build of the whole cable. Since the latter solution, especially for submarine systems, needs very long advance planning and comes with enormous costs, submarine upgrade scenarios are very attractive. Most legacy submarine fibre links are originally designed for and still use 10-Gb/s direct-detection amplitude shift keying (ASK) or DPSK channels, while some already have been upgraded to 40-Gb/s per channel. However, in order to cope with the future capacity demand, also upgrade scenarios for 100-Gb/s channels are discussed and already realized, even for submarine links [1]. In this paper, we report on results of 100-Gb/s field trials over installed legacy 2nd generation submarine fibre links using coherent optical reception with offline digital signal processing (DSP). In the first part, we investigate options to increase the transmission performance of standard DP-QPSK (which is the preferred solution also for today's terrestrial 100G systems) and also discuss their particular implementation efforts. In a second part, we compare the optimized DP-QPSK system to a dual-carrier approach using DP-BPSK modulation.

2. TRANSMITTER SETUP, LINK CONFIGURATION AND RECEIVER

The transmitter which was used for the test channel is assembled from standard laboratory components in order to ensure modularity and maximum flexibility for the generation and comparison of different modulation formats and system configurations. The schematic of the transmitter is depicted in Figure 1.

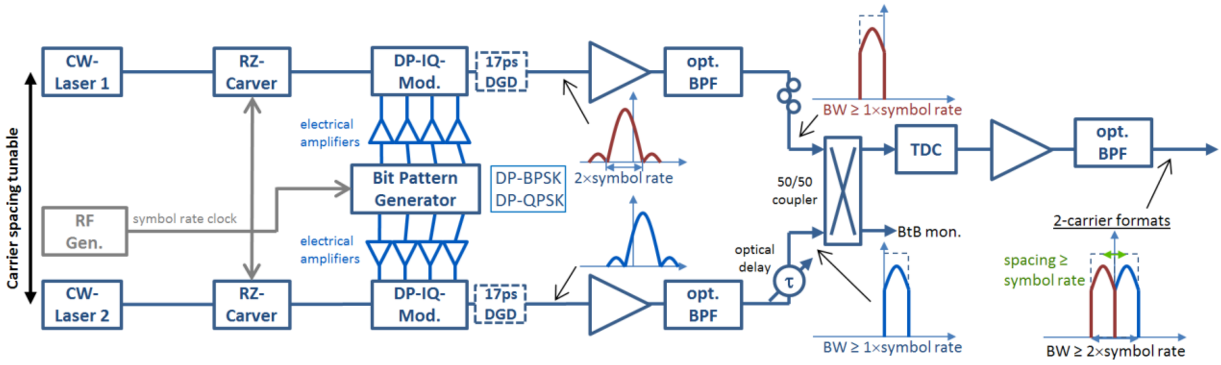

Figure 1: Schematic of the test channel transmitter. (CW: continuous wave, RZ: return to zero, BPF: band pass filter, TDC: tunable dispersion compensator)

The transmitter is able to generate either DP-QPSK or DP-BPSK modulation formats both in a single-carrier or a dual-carrier channel configuration. It is built from two independent modulator rails that are optically combined before the signal is sent to the transmission line. Each modulator rail consists of a free running CW laser (100 kHz linewidth), followed by a Mach-Zehnder modulator (MZM) for RZ pulse-carving and a consecutive optical dual-polarization IQ-modulator. The RZ pulse carver is driven by a symbol-rate clock signal and therefore allows for a flexible generation of different pulse shapes and duty cycles by simply adjusting its drive amplitude and bias setting. The four data tributary signals (PRBS of length 2^{15}-1) per modulator rail are generated with a bit-pattern generator at a symbol rate of 30 GBd. After data modulation and an optional half-symbol DGD element for temporal polarization interleaving, a tunable and steep optical band pass filter is used to limit the bandwidth of each of the two optical sub-carriers individually. Both sub-carriers are then optically combined and an adjustable dispersion pre-compensation is applied to the dual-carrier signal. The generated single- or dual-carrier channel is then merged as a test channel into a 50-GHz spaced WDM comb of loading channels, interleaved from even and odd channels, which were generated by two commercial 100-Gb/s DP-QPSK transponders. For each investigated wavelength of our test channel, three loading channels were switched off to create a spectral gap for the test channel.

Two different transmission links were investigated throughout this field trial, both of them being 2nd generation submarine cables using a mix of NZDSF and SMF as transmission and dispersion-compensating fibers, respectively. The line repeaters have a bandwidth of about 15 nm, an output power of about 11 dBm and a noise figure of about 5 dB. The first link, referred to as link #1, has a length of about 1800 km and an average repeater spacing of about 75 km. The second investigated link (link #2) has a length of about 2900 km and a slightly reduced repeater spacing of about 70 km. Both cable links were looped back at their endpoints using an additional EDFA, effectively doubling their transmission distances to about 3600 km and 5800 km, respectively, and also enabling us to install the transmitter and receiver setup within one cable station.

At the receiver side, the single- or dual-carrier signal is selected from the received WDM comb using a tunable optical filter, coherently mixed with a free running local oscillator laser in a dual-polarization optical 90°-hybrid and then the in-phase and quadrature components of both polarizations are detected with four balanced detectors. The resulting electrical signals are sampled and stored for offline-processing with 80 GS/s using a 4-channel real-time sampling oscilloscope having an electrical channel bandwidth of 36 GHz. However, the combined 3-dB electrical bandwidth of the balanced photo-detectors, connecting RF cables and the real-time oscilloscope was in the order of about 24 GHz (with a smooth 5-dB roll-off towards 36 GHz). The following digital signal processing (DSP) is performed offline with a standard personal computer (PC). It mainly consists of standard DSP routines used in coherent optical transmission systems [2, 3]. These include resampling to an integer number of samples per modulation symbol, correction of imperfections of the optical frontend, FFT-based bulk dispersion compensation, FFT-based offset frequency correction, linear adaptive equalization and polarization separation, SPM phase-noise correction [4], Viterbi&Viterbi carrier phase recovery, differential decoding and finally BER counting.

3. TRANSMISSION PERFORMANCE

The transmission experiments on link #1 are performed to initially investigate the influence of different pulse shapes and also the effect of polarization interleaving on the transmission performance of a 100G single-carrier DP-QPSK system over the given legacy fibre link. These investigations are further used to find the best performing configuration for this single-carrier system which is then compared on link #2 to the dual-carrier approach. First, a dispersion sweep was performed to find the optimum pre-compensation value at the investigated channel frequency of 193.0 THz (1553.33 nm) in the center of the transmission band, which was found to be about 110 ps/nm and which was used for further transmission tests on this particular mid-band channel on link #1. After that, the transmission performance for different signal channel bandwidths for single-carrier DP-QPSK transmission with temporal polarization interleaving was investigated. By adjusting the driving amplitude and bias point of the pulse carver, different RZ pulse shapes were generated. To distinguish between these pulse shapes, the root mean square (rms) spectral bandwidths after the IQ modulator were measured using a standard algorithm of the used optical spectrum analyzer (Advantest Q8384). In Figure 2, the evaluated Q factor (in dB, calculated from counted bit errors) is depicted as a function of the channel bandwidth. For selected spectral widths, the corresponding pulse shapes (without temporal polarization interleaving, measured with a 70-GHz photodiode and sampling oscilloscope) and optical spectra are depicted.

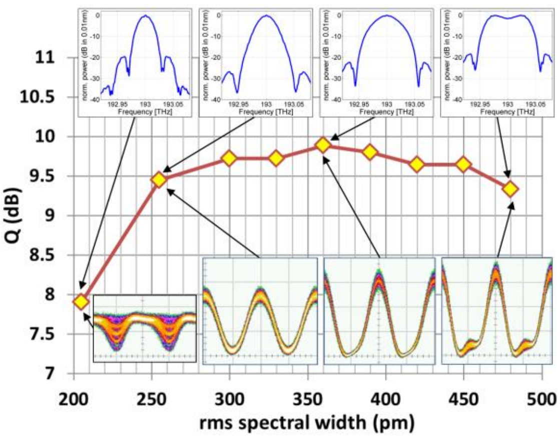

Figure 2: Q factor as a function of the spectral rms width of the DP-QPSK signal. Insets show pulse shapes and spectra before optical filtering.

In our setup, an rms spectral bandwidth of 205 pm represents an NRZ pulse (pulse carver switched off), while increasing values of rms bandwidths indicate RZ pulses with decreasing duty cycles.

It can be seen, that the Q factor after transmission can be improved by nearly 2 dB compared to standard NRZ when choosing the optimum RZ pulse shape, which corresponds here to an rms spectral width of 360 pm. This optimum pulse shaping is then used for further investigations and referred to as pulse-carved RZ (PCRZ) in the following.

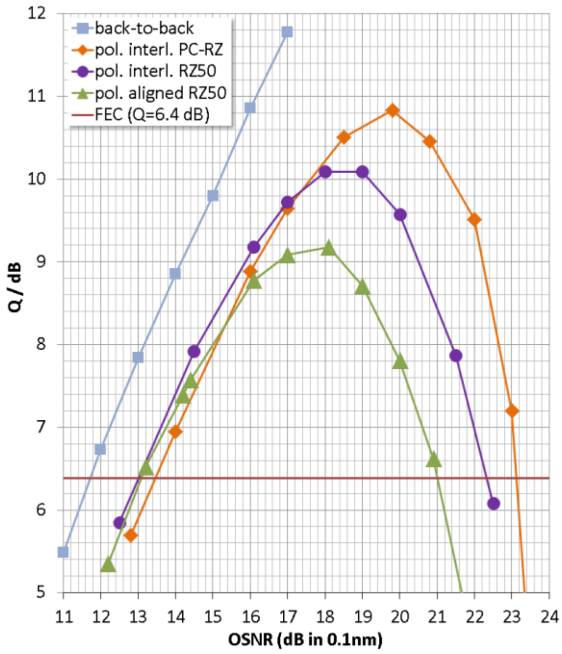

Figure 3: Q-factor as a function of the received OSNR for different configurations on link #1.

Next, the effect of temporal polarization interleaving on the transmission performance is investigated, this time for a data channel in the red (i.e. the long wavelength) part of the C-band spectrum at 192.3 THz. Therefore, again, the optimum pre-dispersion value for this frequency was evaluated to be -566 ps/nm. A comparison between standard RZ pulse shape with about 50% duty cycle and the PCRZ signal is shown in Figure 3, comparing the Q factor after transmission as a function of the received OSNR (which was varied by changing the launch power of the test channel only) for the polarization interleaved and the aligned cases. It is found that both, the transmission performance as well as the optimum channel power, are equally increased by using temporal polarization interleaving. Similar results were already found by using numerical simulations of 100G coherent systems [5]. For RZ signals with a duty cycle of 50%, the performance increase was approximately 1 dB. Using the optimized pulse shape with a spectral rms width of 360 pm increased the Q factor by additional 0.8 dB.

This optimum system configuration for the single-carrier DP-QPSK, namely temporal polarization interleaving and spectral shaping of the signal, is now, in a second investigation, compared to a dual-carrier DP-BPSK setup. This investigation was carried out on link #2 at three selected frequencies (192.3, 193 and 193.9 THz), which represent the red, middle and blue spectral region of the useable bandwidth. This allows for evaluating the performance over the available link bandwidth.

For the dual-carrier setup, pulse shaping was applied to the individual subcarriers. The pulse shape was adjusted to generate flat signal spectra after the IQ-modulators before tight optical filtering. The optical spectra of the individual sub-carriers and the combined dual-carrier channel at the transmitter output are depicted in Figure 4.

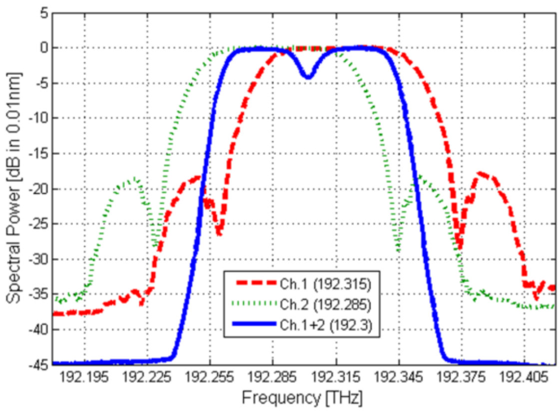

Figure 4: Resulting spectra of the dual-carrier signals at the transmitter: Red and green spectra show the individual subcarriers after pulse shaping and blue spectrum is the filtered dual-carrier channel at the transmitter output.

In order to generate a signal with a high spectral efficiency, we chose the subcarrier spacing to be exactly the symbol rate, which was 30 GHz in this case. However, this resulted already in linear crosstalk between the subcarriers and caused about 0.4 dB back-to-back penalty compared to the single-carrier DP-QPSK case (see also Figure 5). This penalty could be reduced by increasing the subcarrier spacing (at the expense of a lower spectral efficiency) or by using steeper optical filters.

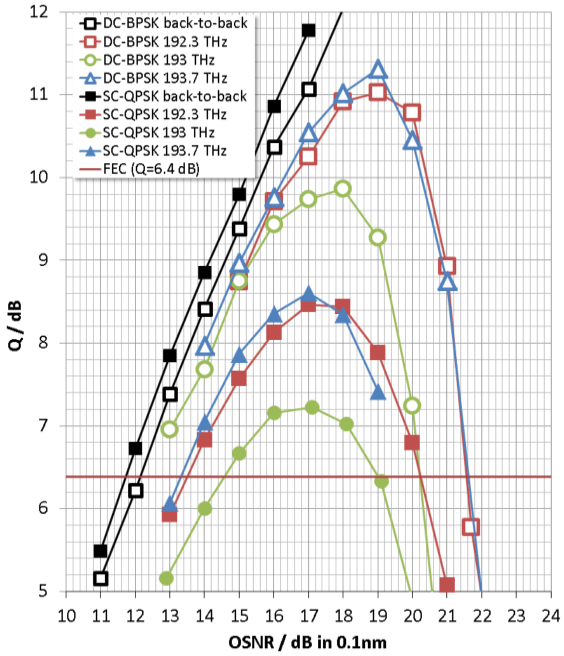

Figure 5: Q-factor as a function of the received OSNR for link #2. Open symbols represent the dual-carrier configurations with separate detection of both subcarriers.

At the receiver side we used the coherent receiver setup described above, while the local oscillator was tuned to the exact frequency of one subcarrier. That means we only processed one subcarrier at a time, then detuned the local oscillator and measured the second subcarrier. The overall BER was calculated by averaging over the individual BERs. In Figure 5, the Q factor as a function of the received OSNR is depicted for both, the single-carrier and the dual-carrier system, for all three investigated wavelength. The pre-dispersion value is optimized for every particular system configuration. First, it becomes apparent that the red band and the blue band wavelength of the individual configurations perform quite similar, while the channel in the mid-band performs more than 1 dB worse. This is a very common behavior of the type of legacy submarine fibre link investigated here [6].

The performance drop of the mid-band channel results from the lower residual dispersion per span at this wavelength and hence more pronounced non-linear interactions compared to the red- and blue-band channels. Further, a significantly improved performance of the dual-carrier transmission compared to the single-carrier transmission becomes apparent. It can be seen, that both, the absolute performance as well as the optimum fibre launch power is increased compared to the single-carrier system, although both systems show theoretically the same linear performance (we even found a penalty of about 0.4 dB for the dual-carrier system, as mentioned above). The measured optimum Q factor of the dual-carrier BPSK channel after 5800 km transmission is better by about 2.5 dB compared to single-carrier QPSK modulation and is a result from the doubled angular separation (180 deg vs. 90 deg) between the constellation points, which make BPSK much more robust against nonlinear phase noise, as typically observed in this type of link.

In order to evaluate the performance penalty due to insufficient receiver bandwidth, we used the same dual-carrier setup as before, but tuned the local oscillator exactly in the center between both subcarriers. By doing so, we were able to receive and process both subcarriers simultaneously. The subcarrier separation was then performed digitally within the DSP routine. Although the electrical bandwidth of the digital sampling scope should theoretically be large enough to detect both subcarriers without additional penalty, we experienced a penalty of about 1.4 dB compared to the separate detection of both subcarriers. We attribute this to the combined bandwidth limitations of the coherent setup (photodiodes and cables) which limits the effective resolution of the higher frequency signal components. Taking these considerations into account, the advantage of the dual-carrier over the single-carrier approach reduces to only about 1 dB.

4. DISCUSSION

The previously investigated methods to increase the transmission performance of 100G systems over legacy submarine fibre links will be reviewed in this section regarding their particular strengths and weaknesses.

RZ pulse shaping, and especially optimizing the particular pulse shape can increase the transmission performance by up to 1.5 dB in the investigated link scenario. However, this comes at the expense of an additional pulse carver.

In contrast to this, the 1 dB increased transmission performance due to temporal polarization interleaving comes nearly without additional costs, since the delay between both polarizations can for example be built into the dual-polarization IQ modulator, tuned for the particular symbol rate.

The use of dual-carrier DP-BPSK instead of single-carrier DP-QPSK results in the most significant improvement of transmission performance and enables 100G transmission with sufficient margins, but requires an almost doubled hardware effort at the transmitter side (depending if one or two lasers are used to generate the two desired optical lines). Furthermore, due to the larger required signal bandwidth and hence decreased spectral efficiency compared to the single-carrier DP-QPSK, the dual-carrier DP-BPSK channel cannot be fitted into the standard 50 GHz channel grid. But not only the increased optical bandwidth requirement is a disadvantage of this approach: In order to avoid two separate costly coherent receivers, this dual-carrier approach imposes a strict demand for higher-bandwidth coherent receiver frontends and increased DSP speed compared to the single-carrier case.

5. CONCLUSION

There are various possibilities to improve the transmission performance of ultra-long-haul 100G transmission systems, even in the case of challenging 2nd generation optical submarine links. We verified the advantage of selected approaches in the investigated link scenario, namely RZ pulse shaping, polarization interleaving and the reduction of modulation order. However, most of these approaches require additional hardware effort and therefore increase the implementation costs. Especially the investigated dual-carrier approach requires a tremendous amount of additional and higher bandwidth hardware.

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