Demonstration of the Improvement of Transmission Distance Using Multiple State Trellis Coded Optical Modulation

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***Abstract*— We demonstrated experimentally the improvement of the transmission distance by 27% of 150Gb/s signal at 3b/s/Hz with a novel TCM format, 8-state 12QAM TCM, compared to PM-8QAM. We also demonstrated improvement of the transmission distance for multiple state TCM using nonlinear compensation, ranging from 14% to 26%, while similar improvement was below 11% for PM signals.**

Keywords—Optical communications, Long haul transmission, Digital signal processing, Coded modulation

I. INTRODUCTION

Internet traffic is still growing at a steady rate in optical backbone networks [1]. This is a prime driver for the increase of the spectral efficiency (SE) in these networks, in order to sustain the collateral increases of CAPEX and OPEX. In recent years, the increase of SE has been enabled by technologies such as digital coherent reception [2, 3], pulse shaping [4], advanced modulation [5] and soft decision forward error correction (SD-FEC) [3]. Furthermore, digital signal processing (DSP) for the demodulation of multiple modulation formats and flexible transponders [6] have enabled the generation and reception of signals with several possible spectral efficiencies (SE). *In fine*, it enables to adapt more finely the maximum achievable capacity to the link length and conditions such as noise and impairments.

In addition to the most common modulation formats like Polarization Multiplexed (PM) Quaternary Phase Shift Keying (QPSK) and PM-Quadrature Amplitude Modulation (QAM) formats, it was demonstrated that using set partitioning (SP) for flexible transponders would enable to gain finer granularity [7, 8] for the optimization of SE, to provide higher capacity depending on specific link condition. Recently, we have proposed to use multiple state Trellis Coded Modulation (TCM) [9-10] in order to realize finer granularity, while using the higher sensitivity provided by TCM in order to gain wider setting ranges with higher capacity. TCM operation steps are used in conjunction with PM formats; however, due to the generation of TCM signals based on SP [11], wider operation ranges TCM steps could not replace and improve performance of traditional PM steps, especially PM-8QAM, which seems an interesting sweet spot for long haul transmission [12].

In this paper, we clarify the performance of TCM signals in 8,000km long haul transmission experiment. We demonstrate a new TCM step at a SE of 3b/s/Hz, 8-state TCM 12QAM based on newly introduced 12QAM constellation [13], for the first time instead of a PM format, PM-8QAM. We demonstrate that it enables to increase the transmission distance at 3b/s/Hz. Furthermore, we clarify equalization of TCM signals; notably, we show that nonlinear compensation [14, 15] substantially improves the transmission performance of TCM signals.

II. MULTIPLE STATE TRELLIS CODED MODULATION

A. *Principle of multiple state trellis coded modulation*

The principle of adaptive transponder based on multiple state TCM is illustrated on figure 1. TCM is realized with an encoder in the transmitter and a Viterbi decoder in the receiver, which are set to the selected number of states using different number of redundancy bits and SP cosets [9, 10]. The number of states and the base constellation are selected depending on the transmission condition, like the received optical signal to noise ratio (OSNR). TCM signals use DSP for modulation and demodulation, which is identical to the base PM format, thus being suitable for adaptive transponder technology.

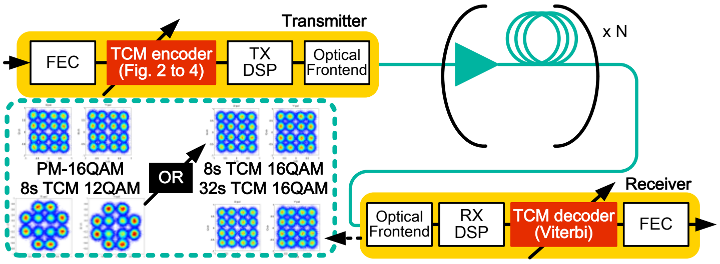

Fig. 1: Principle of multiple state TCM transmitter / receiver

With multiple state TCM, we map N+M bits on the base constellation, where N bits are used to choose between partition sets with SP technique, enabling 2^N cosets of SP [11]; we map the remaining M bits on the chosen SP constellations. Depending on the selected number of cosets, the number of coded bits changes at constant symbol rate, and therefore the SE and *de facto* the system capacity can be adjusted by this operation. Selecting more cosets with less redundancy enables relatively higher capacity, closer to the maximal capacity of the base constellation, whereas selecting fewer cosets with more redundancy enables higher sensitivity with reduced capacity.

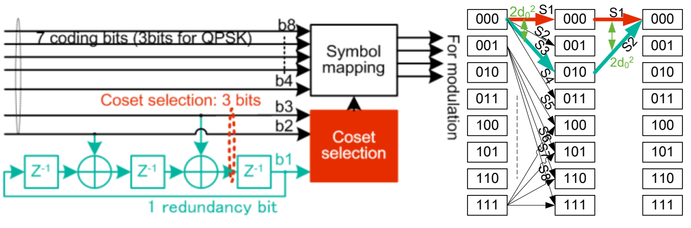

Fig. 2: 8-state TCM 16QAM encoder and trellis diagram

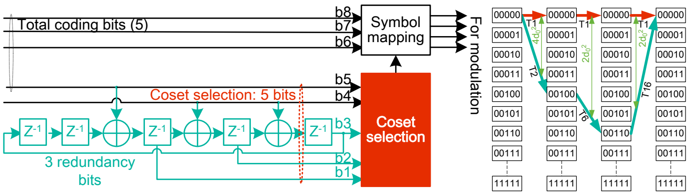

Fig. 3: 32-state TCM 16QAM encoder and trellis diagram

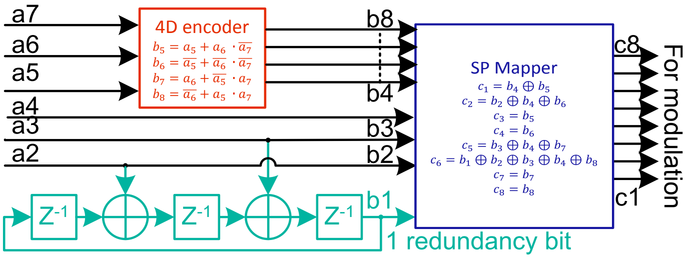

Fig. 4: 8-state TCM 12QAM encoder

B. TCM on QPSK and 16QAM constellations

QPSK constellation enables to generate 2 or 8 cosets for 4 dimensional (4D) TCM. Using 8 cosets enables a higher coding gain than only 2, which offers performance close to SP [9]; therefore in the following development, we only consider a number of cosets higher than 8, with more than 8 states, even for 16QAM constellations. As illustrated on figures 2, 8-state TCM, with 8 cosets, enables to code 3 bits per 4D symbol.

For 16QAM base constellation, we use 8-state TCM with the encoder and the trellis diagram detailed on figure 2. It is fully compatible for QPSK and 16QAM. It has 3 redundancy bits and for 16QAM, it enables to code 7 bits per 4D symbol. In addition, as 16QAM constellation used with two polarizations offers up to 256 4D-symbols, we can go deeper in the SP tree than for QPSK. Therefore we also use 32-state TCM with the encoder and the trellis diagram detailed on figure 3. It has 3 redundancy bits and it enables to code 5 bits per 4D symbol. We have already reported basic evaluation of the back-to-back performance of these structures [9].

C. TCM on 12QAM, based on 16QAM constellations

TCM on 16QAM constellation based on standard SP enables to generate signals with 5 and 7 bits per 4D symbol, using respectively 32-state and 8-state TCM. However, it does not enable to reach signals at 6 bit per symbol directly, using "canonical" set partitions. As SE enabled by coding 6 bits per symbol is reported to offer high capacity for long haul transmission distances, typically transoceanic distances and over [12], using TCM on this type of signal is a laudable goal.

Designing set partitions from 16QAM to code 6 bits per 4D symbols have been demonstrated per polarization but this type of attempt was non optimal and could not surpass PM-8QAM format [16]. Here, we use 8-state TCM based on the set partitioning on 12QAM, which enables to code 6 bits per 4D symbol. The base set partitioning performance surpasses PM-8QAM [13]. As 12QAM constellation is based itself on 16QAM constellation, 8-state TCM 12QAM, *per se*, is constructed with a base 16QAM constellation; thus, it uses common DSP, mapping and 2D decision circuits with other PM and TCM formats based on the same 16QAM constellation.

The encoder is detailed on figure 4. It enables to select 8 cosets from SP on 12QAM, using 2 coding bits and 1 redundancy bit; it also codes 4 bits on the selected coset, therefore coding a total of 6 bits per 4D symbol. We designed the set partitioning of 12QAM from the base 16QAM constellation as follows: first, we removed the four corners of each polarization, leaving 144 4D symbols out of 256; then we removed the combinations of the 4 inner symbols of each 2D constellation, corresponding to the 16 inner 4D symbols, leaving 128 4D symbols; finally, we separated the 4D symbols with SP into 8 cosets of 16 symbols each.

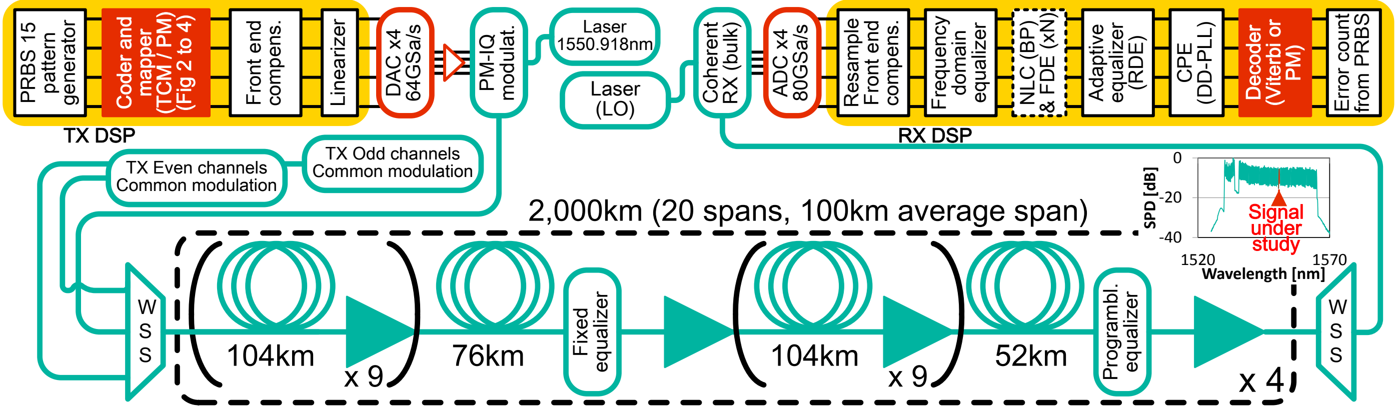

Fig. 5: Experimental setup of WDM transmission of TCM and PM signals

III. EXPERIMENTAL VALIDATION OF MULTIPLE STATE TCM WITH ULTRA LONG HAUL WDM TRANSMISSION

A. Experimental setup for the validation of transmission of multiple state TCM

The experimental setup used for the validation of the transmission of multiple state TCM signals is summarized on figure 5. It was composed of a transmitter and a receiver, which feature offline DSP [9] and of a long haul straight transmission line. Two additional transmitters were used to generate common modulated signals used as 83 WDM neighbors.

The transmitter was composed of 4 Digital to Analog Converters (DAC) generating 32Gbaud signals at 2 samples per symbol, which were used to drive a PM Cartesian (IQ) modulator, controlled with auto bias circuit. The symbol rate of 32Gbaud assumes 20.5% FEC overhead over several tributaries at 25Gbaud. The offline DSP featured generation of signal based on PRBS 15 patterns, coding for TCM and PM formats according to encoders of figures 2 to 4, mapping on the base 2D constellations and equalization of the optical frontend imperfections, including limitations of bandwidth and linearity.

The receiver was composed of a bulk coherent mixer with a set of 4 balanced photodiodes, a digital oscilloscope used to sample the received signals at 80GSa/s. The digitalized data was processed offline with resampling at 2 sample per symbol, compensation of optical frontend imperfections, compensation of chromatic dispersion using overlap Frequency Domain Equalization (FDE) [17], adaptive equalization and polarization de-multiplexing with Radius Directed Equalization (RDE) after pre-convergence with Constant Modulus Algorithm (CMA), Carrier Phase Estimation (CPE) with Decision Directed Phase Locked Loop (DD-PLL), decoding with Viterbi decoder or PM decoding and error counting on the PRBS 15 patterns.

The transmission evaluation was realized with 84 channels spaced by 50GHz; they were generated with three transmitters, including one for the generation of the signal under study and two others for the generation of remaining even and odd WDM channels by common modulation. The same modulation format and coding schemes were applied to the signal under evaluation and to all the WDM neighbors, to evaluate homogeneous WDM transmission. Wavelength multiplexing and de-multiplexing were performed with Wavelength Selective Switches (WSS). The signals were transmitted through a straight line of 8,000km composed of 80 spans of low loss pure silica core fiber, with long spans of average length of 100km and Erbium Doped Fiber Amplification (EDFA) only. Fixed and programmable equalizers were added every block of 2,000km.

B. Transmission results of multiple state TCM signals

We first consider QPSK base constellation; the transmission results for 100Gb/s PM-QPSK at 2b/s/Hz and for 75Gb/s 8-state TCM QPSK at 1.5b/s/Hz are plotted on figure 6, for their optimal launch power, without using Back-Propagation (BP). We could not count error below 2,600km for PM-QPSK and below 5,600km for its TCM counterpart. Considering an operation Q value of 8.5dB, which would include 2.1dB margin over a 6.4dB FEC limit at 32Gbaud [3], transmission over 8,000km is possible with PM-QPSK; therefore the Q improvement above 1.6dB enabled by 8-state TCM would be useful at distances longer than 8,000km, potentially in the range of 10,000km as extrapolation would suggest.

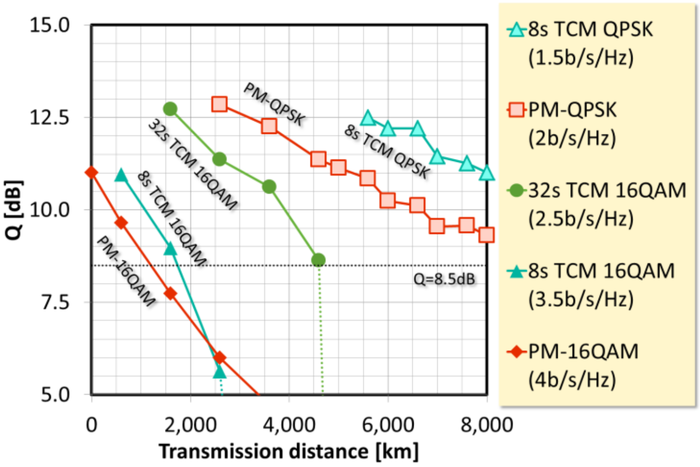

Fig. 6: WDM transmission results for PM and TCM signals at 32Gbaud

Moreover, the results of transmission of 16QAM base constellation signals are also plotted on figure 6, without BP, for their optimal launch powers, which were equal. For 125Gb/s 32-state TCM 16QAM, considering an operation at a Q of 8.5dB, the maximum possible transmission distance was 4,600km. As observed in back to back configuration, demodulation of the base 16QAM constellation limits the minimum achievable Q value for this TCM signal [9, 10]. However, it still offers an interesting operation setting for distances lower than 4,600km, offering a 25% capacity improvement compared to PM-QPSK.

On the other side, for 200Gb/s PM-16QAM and considering operation at a Q of 8.5dB, we could verify this condition up to 600km due to the rough granularity of evaluated distances; however, interpolation indicated a possible operation up to 1,200km. In comparison, 175Gb/s 8-state TCM 16QAM could offer operation at 8.5dB of Q for distances up to 1,600km. Although the distances are greatly reduced for these formats, they offer higher capacity due to their higher SE of 3.5b/s/Hz and 4b/s/Hz.

C. Transmission results of 8-state TCM 12QAM signals at SE of 3b/s/Hz and comparison with PM-8QAM at equal SE

We compared the results of WDM transmission for 8-state TCM 12QAM and PM-8QAM, as summarized on figure 7. Both formats offer the same payload of 150Gb/s and the same SE of 3b/s/Hz in a 50GHz grid; this is the first time that PM and TCM optical signals are compared at identical SE. Besides, contrary to 8QAM, 12QAM based format offers compatibility with its base 16QAM constellation, which simplifies design of a flexible transponder.

Again, considering operation at Q above 8.5dB, which comprises operation margin above a FEC limit of 6.4dB, we could verify distances up to 3,600km for 8-state TCM 12QAM and up to 2,600km for PM-8QAM, which is 1,000km shorter.

Using interpolation to circumvent the rough distance granularity, 8-state TCM 12QAM could offer up to 4,180km against 3,300km for PM-8QAM. This represents an improvement of 880km brought by 8-state TCM 12QAM over PM-8QAM, i.e. 27% enhancement from 3,330km. 8-state TCM 12QAM offered sensitivity improvement compared to PM-8QAM for Q above 6.2dB. Thus, 16QAM constellation based 8-state TCM 12QAM enables to increase the transmission distance compared to PM-8QAM at constant SE.

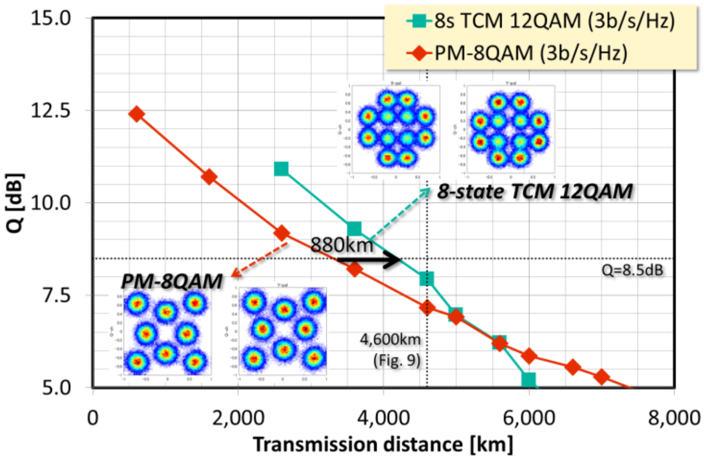

Fig. 7: WDM transmission results for 8-state TCM 12QAM and PM-8QAM

IV. IMPROVEMENT OF THE RECEPTION SENSITIVITY WITH COMPENSATION OF LINEAR AND NONLINEAR EFFECTS ON TCM SIGNALS

A. Optimized linear equalization on TCM signals

We analyzed adaptive equalization, which we used in order to improve transmission performance reported on figures 6. For this purpose, we limited the study to linear effects in back-to-back configuration at constant OSNR of 20dB/0.1nm and we reduced bandwidth of the transmitter and receiver frontends below 16GHz, for larger inter symbol interference.

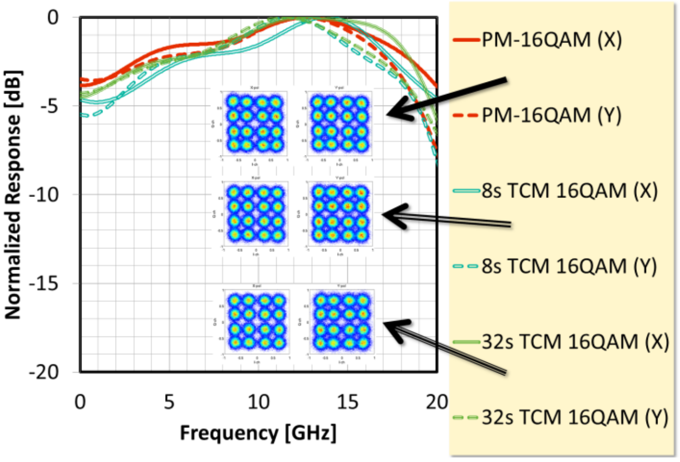

Fig. 8: Frequency response of the linear equalizer with TCM and PM signals

Figure 8 illustrates the frequency response of the adaptive equalizer in receiver DSP, for compared signals, here PM-16QAM, 8-state TCM 16QAM and 32-state 16QAM. The insets represent the 2D constellation for these formats; clearly they all have similar shapes. We verified that all formats could use the same DSP algorithm, although individual algorithm parameter adjustment provides optimal performance. Moreover, the similar filter shape, characterizing high pass filter to compensate for the bandwidth limitation, shows that TCM and PM formats could be equalized with the same DSP algorithms, which simplifies design of adaptive transponders.

B. Improvement of the transmission distance using compensation of nonlinear effects on TCM signals

Finally, we investigated the improvement in transmission length, which digital back-propagation enables on the transmission results of TCM and PM signals. We applied BP [14, 15] to the data by dividing the FDE block of figure 5 and including nonlinear compensation (NLC) stages, which compensate for self-phase modulation (SPM) impairing the signal during transmission.

First, we compared transmission results at 4,600km for PM-8QAM and 8-state TCM 12QAM for different numbers of NLC stages. For both formats, saturation in performance appears at 3 stages of NLC. Whereas the improvement is limited to 0.43dB for PM-8QAM, it enables up to 1.12dB of improvement of 8-state TCM 12QAM, allowing to overpass 8.5dB at the distance of 4,600km. Indeed, TCM is more susceptible to suffers from nonlinearity, being prone to burst errors from signal correlation; this allows more improvement in return from NLC for TCM compared to PM at same SE.

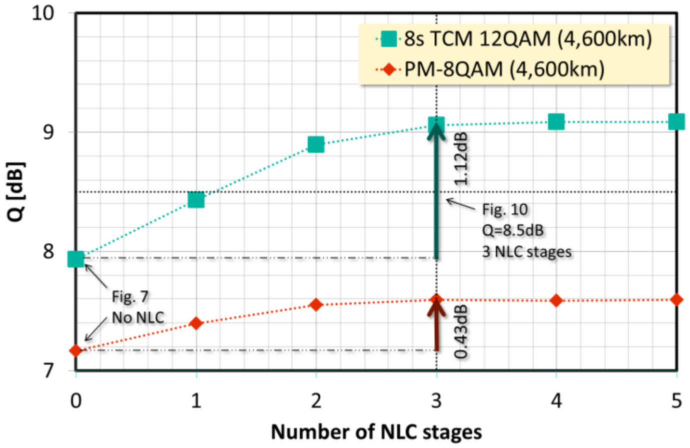

Fig. 9: Improvement of sensitivity after 4,600km transmission with BP

Consequently, we applied 3 stages of NLC to transmitted data of figure 6 and 7 and we estimated by interpolation the transmitted distance at a value of Q=8.5dB. The results are summarized on figure 10, as possible operation at 8.5dB with achievable SE against estimated transmission distance. For comparison the data without NLC is also plot, as well as PM-8QAM data as a PM reference.

For SE of 4b/s/Hz with PM-16QAM, BP only enabled to improve the transmission distance by 80km to 1,280km, due to the short distance, where the accumulation of nonlinearities is limited. This represents an improvement of 7%. While SE of 3.5b/s/Hz was achievable with 8-state TCM 16QAM up to 1,740km, BP enabled to increase this distance by 450km to

2,190km. This represents an improvement of 26%. Considering SE of 3b/s/Hz with 8-state TCM 12QAM, BP enabled to extend the estimated distance by 580km, to 4,760km, *i.e.* a 14% increase. In comparison, the distance improvement by BP at identical SE with PM-8QAM was only 350km, for an 11% increase; this illustrates the fact that BP benefits more to TCM than to PM signals. Finally, SE of 2.5b/s/Hz was achievable up to 4,600km and BP enabled to extend this distance by 830km to 5,430km, *i.e.* a 18% increase. Thus BP with 3 stages of NLC enables to increase the transmission distance of 16QAM constellation based TCM signals and BP benefits more to TCM signals than to PM signals.

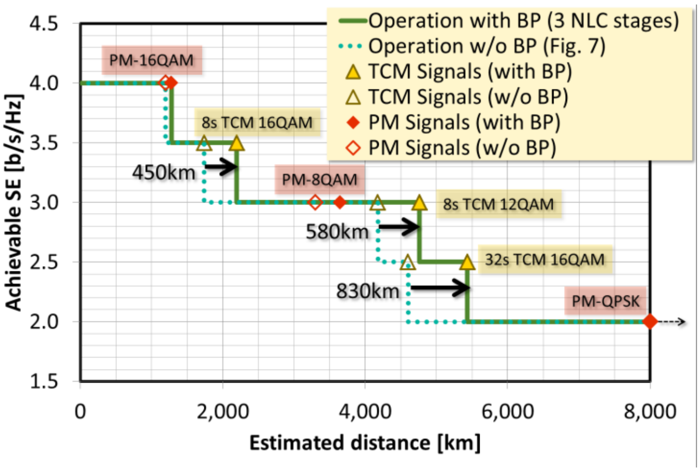

Fig. 10: SE versus estimated transmission distance for operation at Q=8.5dB and increase of the distance with BP

V. CONCLUSIONS

We have experimentally demonstrated, for the first time, 8-state 12QAM TCM as a new TCM step, based on a 16QAM constellation, which can be used instead of a PM format, PM-8QAM. Both signals had payload of 150Gb/s at 3b/s/Hz. We have demonstrated that 8-state TCM 12QAM enabled to increase the possible transmission distance at 3b/s/Hz by 880km, to 4,180km at Q=8.5dB. This represents an increase of 27%.

Furthermore, we have demonstrated that BP increased the transmission distances of 16QAM constellation based TCM signals, ranging from 450km to 830km depending on SE, representing increases from 14% to 26%. We have shown that BP benefited more to TCM signals than to PM signals, which was below 11%.

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