Scattered Pilot Channel Tracking Method for PDM-CO-OFDM Transmissions Using Polar-Based Intra-Symbol Frequency-Domain Average

Wei-Ren Peng, Koki Takeshima, Itsuro Morita, Hidenori Takahashi, and Hideaki Tanaka

KDDI R&D Laboratories Inc., 2-1-15 Ohara, Fujimino-shi, Saitama 356-8502, Japan
Tel: +81-492-7809, Fax: +81-492-7821, E-mail: xwe-peng@tsm.kddilabs.jp

Abstract: We have demonstrated an efficient scattered pilot channel tracking approach with a new polar-based intra-symbol frequency domain average (ISFA) for 16-QAM, 40-Gb/s PDM-CO-OFDM systems. This proposal could promise an relatively stable performance even under an rapidly time-varying environment.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

Coherent transmission, due to its robustness against all the linear impairments throughout the link, has long attracted lots of interest in optical long-haul applications. Contrary to the single-carrier transmission, the coherent multiple-carrier transmission, i.e. coherent optical orthogonal frequency division multiplexing (CO-OFDM), has a well-defined power spectrum enabling the super-channel transmission that achieves an ultra-high spectral efficiency [1-3]. With the use of both polarizations, the polarization-division-multiplexing (PDM) CO-OFDM can easily double the data capacity while keeping the same signal bandwidth with a moderate complexity [1-3]. Therefore, PDM-CO-OFDM has become one of the most promising formats worthy of further investigations.

Due to the periodically-inserted training symbols in PDM-CO-OFDM [4], the channel response can be continuously tracked and updated, and hence the signal quality can be maintained even under a strong influence of polarization mode dispersion (PMD). Conventionally, all the subcarriers in the training symbols are dedicated for channel estimation, which could enhance the reliability of the derived channel response on each single subcarrier. However, the channel response usually would not exhibit a strong difference across the subcarriers in proximity. Hence, it is possible to utilize only the partial scattered subcarriers of the training symbols to estimate the scattered channel responses, which later could be used for deriving the complete channel responses via interpolations. Obviously, this approach could offer either of the following benefits: 1) with a given training period, the required training overhead could be reduced, or 2) with a given training overhead, the training period could be reduced leading to a more robust PMD tolerance. Hereafter we will mainly focus on the exploration of the later one: reduced training period with a fixed training overhead.

In this paper, we have demonstrated the scattered pilot channel tracking (SPCT) method for 16-QAM, 40-Gb/s PDM-CO-OFDM systems. This method firstly obtains the scattered channel responses for the pilot subcarriers, then uses the proposed polar-based intra-symbol frequency domain average (ISFA) method [5] for enhancing the estimation reliability, and finally acquires the full channel responses via interpolations. The performances for the conventional and the proposed methods are compared: 1) with the back-to-back OSNR sensitivity, 2) after 320-km

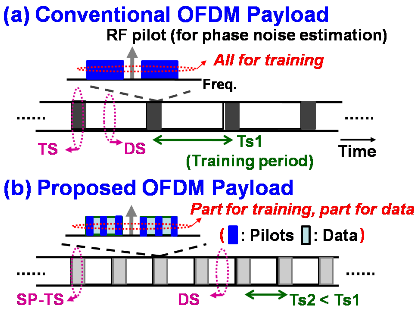

Fig. 1 Concept of the scattered-pilot channel tracking method. TS: training symbol, DS: data symbol, SP-TS: scattered-pilot training symbol.

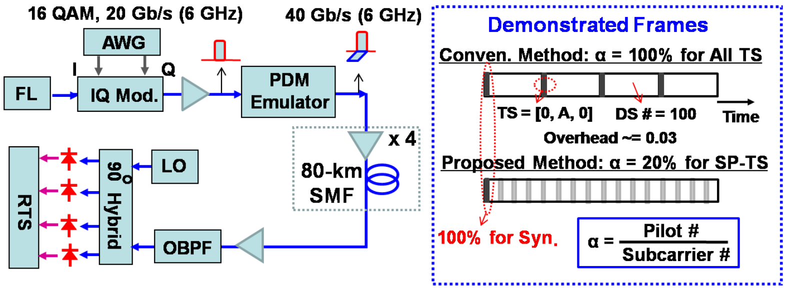

Fig. 2 Experimental setup and the demonstrated frames for 40-Gb/s PDM-CO-OFDM system. FL: fiber laser, AWG: arbitrary waveform generator, RTS: real time scope. α: pilot filling ratio.

standard single mode fiber (SSMF) transmission, and 3) with a PMD rapidly-varying environment. Given a training overhead, the proposed method with a 20% pilot filling ratio offers a comparable performance with the conventional one when under an relatively static channel; while it outperforms the conventional one by ~4 dB when under a PMD rapidly-varying channel.

2. Working Principle and Experimental Setup

Fig. 1 depicts the conventional and the proposed channel tracking methods for CO-OFDM systems. In the conventional method (Fig. 1(a)), the training symbols (TS, or conventional training symbols, CTS), which utilizes all the subcarriers for tracking purpose, are inserted periodically into the OFDM payload with a period of Ts_1. Later at the receiver the previously-proposed Cartesian-based ISFA (CISFA) method [5], which refines the channel estimations by making full use of the channel coherency for subcarriers in proximity, can be applied for enhancing the estimation reliability, that is,

$$\overline{H}(k) = \frac{1}{M}\sum_{k-m}^{k+m}\mathrm{Re}\{H(k)\} + \frac{j}{M}\sum_{k-m}^{k+m}\mathrm{Im}\{H(k)\}$$

where $\overline{H}(k)$ and $H(k)$ are the refined and raw channel estimations, respectively, k is the subcarrier index, and $M = (2m+1)$ is the subcarrier number for average.

In the proposed SPCT method (Fig. 1(b)), the scattered-pilot training symbols (SP-TS), which utilize only partial subcarriers, or pilots, for training and release the other subcarriers for carrying data, are uniformly inserted within the OFDM payload with a period of Ts_2. For convenience we define the pilot filling ratio as α = (pilot number) /(subcarrier number) for the SP-TS, and the SP-TS will degenerate to the CTS when $\alpha = 100\%$. Given the same training overhead, the SP-TS should appear more frequently than the TS in the conventional method, i.e. $Ts_1 > Ts_2$. Similarly, to increase the reliability of the channel estimations, the ISFA could be used as well for the SP-TS. However, with the consideration of the diminishment of the phase coherency between adjacent pilots, we suggest using the polar-based ISFA (PISFA), which refines the raw channel estimations with their polar form as follows:

$$\overline{H}(k) = \left(\frac{1}{M}\sum_{k-m}^{k+m}\left|H(k)\right|\right)\times \exp\left[\frac{j}{M}\sum_{k-m}^{k+m}\arg\{H(k)\}\right]$$

Notably, k here only represents the pilot index and the function **arg**{.} takes the phase term and unwrap it. The PISFA could support those training subcarriers with great phase differences, which would happen in situations of: 1) using a small FFT size or the proposed SPCT method, or 2) suffering a great amount of accumulated chromatic dispersion (CD). After PISFA, interpolations will be utilized to obtain the complete channel responses of all subcarriers.

Fig. 2 depicts the experimental setup. A 10-kHz linewidth fiber laser (FL) is used as the transmitter light source, and its output is modulated with the electrical OFDM signal via an in-phase/quadrature-phase (I/Q) modulator. The OFDM signal is generated offline with Matlab and composed of frames with different architectures shown in the right side of Fig. 2: a) conventional method, which periodically inserts 4 CTS into an OFDM payload containing 400 data symbols (DS), which leads to a training overhead of 0.03, b) proposed method, which applies one CTS at the head for synchronization, and inserts 15 SP-TS ($\alpha = 20\%$) uniformly into the OFDM payload, resulting in the same overhead of 0.03. Similarly, frames with 5% and 10% SP-TS are generated as well for later comparisons. Note that the training periods, in units of the DS number, for the conventional method (100%) and the proposed methods with 20%, 10%, and 5% SP-TS are 100, 27, 13, and 7, respectively, for maintaining the same training overhead.

For each DS, binary data is randomly generated and modulated onto 520 subcarriers with 16-QAM format, which is zero-padded to a fast Fourier transform (FFT) size of 1024. After Inverse FFT (IFFT), a length of 10-point cyclic prefix (CP) is added to every OFDM symbol, leading to 1034 points per symbol. The OFDM waveform is then loaded into an arbitrary waveform generator (AWG) which has its “real” and “imaginary” outputs driving the IQ modulator with a 10 GS/s sampling rate. Hence, the raw data rate of the output signal is ~20 Gb/s occupying a bandwidth of ~6 GHz. The I/Q modulator is biased at the point slightly away from null to arrange an RF-pilot tone for phase noise estimation [4].

Later a PDM emulator, which splits the light into two branches, has one branch delayed by ~1-OFDM symbol duration (~103 ns), and combines the two outputs orthogonally in polarization using a polarization beam combiner, is used to emulate a polarization diversity transmitter with a data rate of 40-Gb/s. The output of PDM emulator is then launched into 4 spans of 80-km SSMF. After 320-km SSMF transmission, at the receiver the signal is pre-amplified with an EDFA, filtered with an optical band-pass filter (OBPF), and heterodyne-detected with a 100-kHz linewidth local oscillator (LO, located at ~5 GHz away from the FL output frequency) through an optical 90^{o} hybrid. The optical “real” and “imaginary” components of both orthogonal polarizations are recorded by a real time scope (RTS) operated at 50 GS/s. Down-conversion, phase noise compensation, synchronization, cyclic prefix removal, FFT, and channel estimation and equalization with ISFA are conducted offline with Matlab program. Linear interpolation, due to its very simple algorithm and acceptable performance, is applied for obtaining the full channel responses in the proposed method. The bit error rate (BER) is evaluated with the direct error counting approach and the Q factor is derived from the measured BER.

3. Results and Discussions

In Fig. 3, we firstly compare the performances of using the CISFA and PISFA for conventional and proposed methods. To consider the accumulated CD effect, we transmit the measured back-to-back signal waveform in the computer over the virtual fiber, which only contributes the linear CD with *D* = 16 ps/[km.nm]. Note that such kind of virtual impairment is considered only for Fig. 3 throughout this paper. The used average number for 100% (hereafter we will call the conventional method simply as 100% SP-TS), 20%, and 5% SP-TS are 21, 9, and 3, respectively, which are found to be optimum in back-to-back. It is found that the 100% SP-TS has similar performances with CISFA and PISFA; while the 5% and 20% SP-TS exhibit better performances with PISFA, especially for the 5% SP-TS, which even yields an ~0.5 dB gain in back-to-back. This demonstrates that PISFA is less sensitive to the phase difference among adjacent training subcarriers and therefore can offer a better performance when with the lower-percentage SP-TS and/or under the influence of a great amount of accumulated CD. Based on the observations, we use CISFA for the 100% SP-TS and PISFA for the proposed methods in the following measurements.

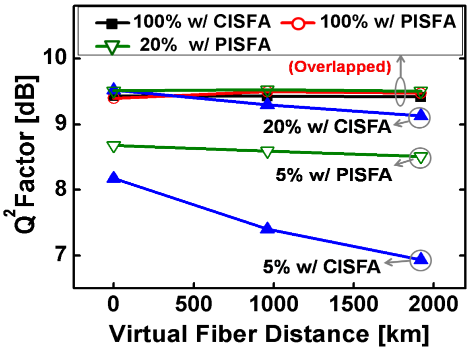

Fig. 3 Q factor vs. virtual fiber length. Virtual fiber introduces only the CD (*D* = 16 ps/[nm.km]) to the received signal in the computer. 100% (pilot filling ratio) is with the conventional method, and the 20% and 5% are with the proposed method. OSNR = 14 dB / 0.1 nm.

Fig. 4 depicts the measured sensitivity with the conventional and proposed methods. We found the 20% SP-TS exhibits a < 0.2 dB penalty relative to the 100% SP-TS; while 5% and 10% SP-TS are found to have ~1 and ~2 dB worse sensitivity, respectively, and tend to have error floors when OSNR > 24 dB.

In Fig. 5 we further compare their performances with 320-km real fiber. Once again the 20% SP-TS has a very similar performance with the 100% SP-TS, showing that the Q penalty is < 0.2 dB over diverse launch power.

To test the signal robustness against the channel variations, the transmission fiber is replaced with a polarization scrambler (PS) which changes the polarization state by a controllable amount per 10 us. Shown in Fig. 6 is Q factor vs. the polarization rotation speed, in terms of the step angle per 10 us. The 5% SP-TS offer a very robust tolerance against the time-varying channel while the conventional 100% SP-TS has the worst tolerance due to its longer training period. Particularly, using 20% SP-TS could outperform the 100% SP-TS by 4 dB when the polarization step angle = ~ 0.6 rad.

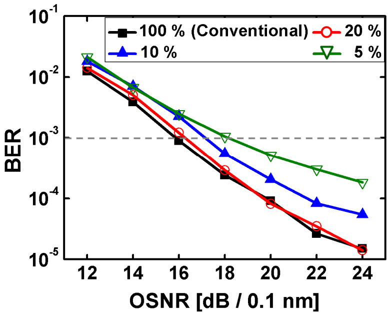

Fig. 4 OSNR sensitivities with the 100% (conventional), 20% 10%, and 5% SP-TS.

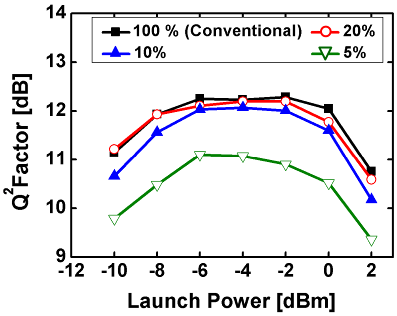

Fig. 5 Q factor vs. launch power after 320-km real SSMF fiber.

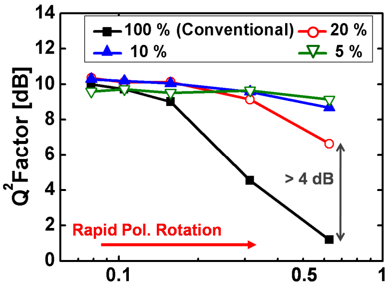

Fig. 6 Q factor vs. polarization scrambling speed. OSNR = 18 dB/0.1nm.

4. Conclusions

We have demonstrated the SPCT method with PISFA. With 20% pilot filling ratio, the system offers a similar performance compared with the conventional one under an relatively slow-varying channel; while it outperforms the conventional one under a PMD rapidly changing channel.

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