A Tracking-free PDM Mobile Fronthaul with High SOP Perturbation Tolerance

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Abstract: *A PDM mobile fronthaul was demonstrated with doubling capacity via a polarization tracking-free de-multiplexing module. 59.2-Gb/s data rate and 32.5-dB power budget were achieved even signals suffering from rapid SOP changing rate of 2,000 degrees/ms.*
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I. Introduction

One of the major challenges of the next generation 5G wireless networks is increasing the throughput of the legacy orthogonal frequency division multiplexing (OFDM) based systems for the tremendous growth of mobile applications [1]. Currently digital based mobile fronthaul (MFH) interface, e.g., common public radio interface (CPRI) [2], suffers from low bandwidth efficiency. Therefore, analog radio-over-fiber (A-RoF) accompanied with carrier aggregation technique attracts many attentions due to its higher spectral efficiency and simplified receiver implementation for facilitating dense small cell deployment of fiber-wireless convergence [3]. To further enhance the channel capacity of A-RoF systems, a straightforward solution is increasing the modulation level. For example, to double the transmission throughput of 16-QAM systems, we must apply 256-QAM. However, the vertical resolution of the digital-to-analog (D/A) convertor and the linearity of the boost amplifiers restrict the achievable signal-to-noise ratio (SNR) and the employable QAM level of practical systems. While, polarization division multiplexing (PDM) technique, which is compatible with OFDM format, is another promising solution for system capacity doubling. However, the state-of-polarization (SOP) of the received PDM signal is randomly changing over time and link distance since the fiber infrastructures underground are suffered from fiber vibrations, pressure and temperature variations of the surrounding environment, etc. Therefore, to de-multiplexing PDM signals in the receiver side, a dynamic polarization tracking with SOP monitoring and feedback control, [4] or a multiple-input multiple-output digital signal processing (DSP) implemented with balanced detectors [5] are required. Both result a complicated and costly design and thus limit their feasibility in a cost-sensitive MFH.

In our previous works, we demonstrated a high A-RoF compatible PDM-OFDM MFH with passive polarization de-multiplexing module in the remote unit [6] to double the service coverage. As shown in Fig. 1, by applying dual-polarized signals with a single-polarized optical carrier, the proposed PDM-OFDM scheme can double the channel capacity without additional software and/or hardware modification at remote radio units (RRUs). In this work, we further evaluate the functional area of the proposed scheme achieving via a Faraday rotating mirror (FRM) and the tolerance of SOP variations. We also indicate in this paper that an optical coupler is essential for circumventing performance degradation in this passive polarization de-multiplexing scheme. Finally, a 59.2-Gb/s PDM-OFDM MFH is achieved with 32.5-dB power budget over 50-km transmission even PDM signals experiencing a fast SOP changing rate of 2,000 degrees/ms.

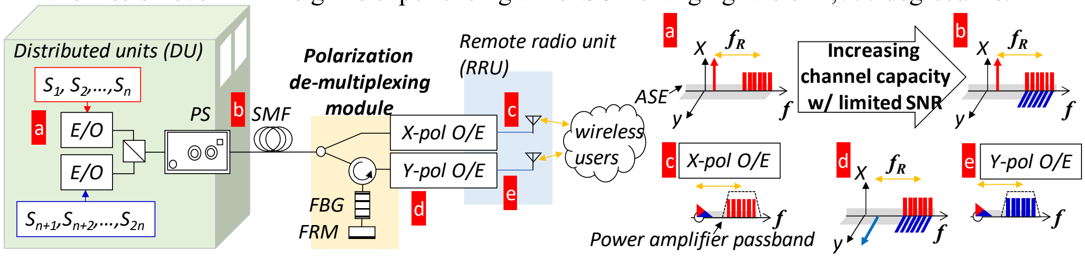

Fig. 1. Conceptual diagram of the proposed A-RoF compatible PDM-OFDM MFH. (a) The conventional single-polarized MFH signal. (b) The proposed PDM-OFDM MFH output. (c-e) Optical and electric spectra at corresponding points. PS: polarization scrambler.

II. Operation Principles and Experimental Setup

SOP of transmitted signals is prone to change even in a lab environment without significant fiber vibration or pressure variation. Figure 2(a) exhibits SOP variation among 1 and 8 hours at back-to-back (BTB) and after 50-km fiber link. The SOP is stable in the BTB scheme, on the other hand, the longer transmission distance scheme is more sensitive to the fiber bending and temperature perturbation causing an un-controllable SOP change over time. Active PDM de-modulation scheme must typically tracks the SOP change and compensate it at the receiver-end. While, by delivering dual-polarized OFDM signal with single carrier of our proposed scheme, the SOP tracking is unnecessary. One of the key elements of the proposed scheme is FRM, which can be modeled by Jones matrix of linear combining non-reciprocal Faraday rotator with 45° and a mirror [7]:

$$FRM = [F(-\theta)][Mirror][F(\theta)] = \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} \tag{1}$$

In general, FRM can be consider as a polarization ortho-conjugator. However, since Eq(1) is a 2-by-2 matrix, there are theoretically two eigen-polarizations which remain the same value after passing through the FRM. Therefore, we firstly correct our previous statement of FRM in [8], the FRM should have two singularities and result a limited functional area. To evaluate this issue, we let two orthogonal carriers passing though the proposed passive PDM de-multiplexing module to become parallel SOP. Figure 2(b) shows the received powers of different input SOP scanned around the singularities on the Poincaré sphere in different viewing angle (i.e azimuth angle=120°, 90°; elevation angle=15°, 0°). We can see that the eigen-modes marked in red are at the 2 poles of the sphere with around -70 dBm power as indicated in Fig. 2(c). The transition area marked in green have around -60 dBm received power, and rest of the area are defined as the functional region with the received power of -52.5 dBm. A high percentage of functional area (including blue-marked points and the rest of unmarked region) implies FRM can work properly for most scenarios of SOPs.

We believe that the area of the transition zone in this demonstration is mainly related to the direct reflection path of fiber Bragg grating (FBG) induced polarization rotation, and it can be minimized if the proposed PDM de-multiplexing module becomes a totally integrated device. Meanwhile, for practical applications, two possible solutions to overcome a long-term transmission fails by two singularities of FRM are (i) a feedback control via polarization state information from the RRUs and (ii) applying a polarization scrambling (PS) to avoiding SOP stay at the singularities. The probability of FRM working cases over time is investigated via the aforementioned orthogonal carrier method with randomly 1-deg/s scrambling rate over the whole Poincaré sphere and the 1-hours measurement is depicted in Fig. 2(c). We observe that in most of time the received power is stick on the maximum value, and only one un-functionable case is measured. The power fluctuation of the minimum received power is caused by the thermal noise of the employed photodetector (PD).

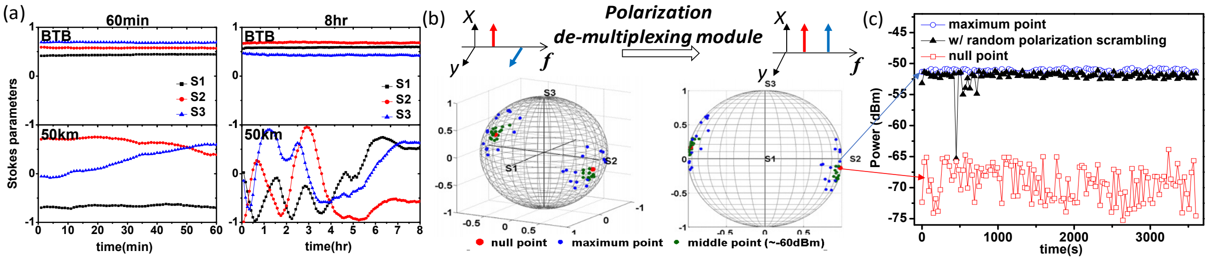

Fig. 2. (a) SOP measurement over 1 and 8 hours in a lab environment. (b) Singularities of FRM (red-markers) (c) Probability of FRM working case (maximum received power) over 1hours.

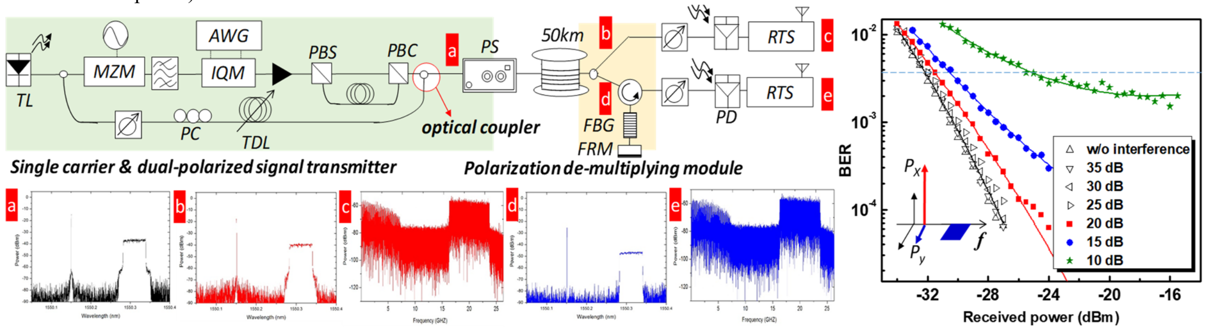

Fig. 3 Experimental setup of the proposed A-RoF PDM-OFDM MFH (a-e) Optical and electric spectra at corresponding points.

Figure 3 exhibits the experimental setup of the proposed PDM-OFDM MFH. A tunable laser at 1550.15 nm is applied. The optical OFDM signal is generated via a carrier insertion mechanism for optimizing optical carrier to signal power ratio (CSPR) of 1 dB [6]. In the upper path of the proposed transmitter, an intensity modulator in conjunction with a single-side band optical filter is operated at the carrier suppression (OCS) mode for achieving a 20-GHz frequency up-conversion. The up-converted frequency can be modified depending on the application requirement. The offline encoded OFDM signal is followed by the ordinary DSP processing [6,8] and generated via a 12 GSa/s arbitrary waveform generator (AWG) with 8-bit resolution. 316 subcarriers are employed for carrying 16-QAM data over 512 FFT size, and thus the designed OFDM signal occupies about 7.4 GHz bandwidth and carries 29.6 Gb/s data in a single-pol. To fully utilize the valuable spectral resources of the AWG, an IQM is applied and biased at its null points to operate in the field-modulation mode. Constrained by the instruments, PDM signals are generated via a polarization beam splitter (PBS), polarization beam combiner (PBC) and a de-correlating optical delay for aggregating a dual-pol 59.2 Gb/s OFDM data. In the lower path, the SOP of the optical carrier must align in the x-pol to mitigate the interference of y-pol OFDM data in the x-pol reception-end. This alignment can be verified at the output of the transmitter by minimizing the beating term of x-pol carrier and y-pol signal after PD and its detailed mechanism was specified in our previous work [8]. A PS is applied to randomly scramble the output SOP for mitigating the long-term fails in the situation of PDM signals stay at eigen-points.

After 50-km fiber transmission, the proposed PDM-OFDM are split into two paths for x-pol and y-pol data de-modulation, respectively. For the upper RRU, the dual-pol data is directly detected via a single-end PD with x-pol optical carrier and then sampled by a RTS. In the lower path, the optical signals are routed via an optical circulator and fed into a FBG to sift out the x-pol carrier for the polarization ortho-conjugating manipulation. To compensate the additional phase mismatch induced by the PDM module in the transmitter, an optical delay line is embedded between FBG and FRM with only half-length of the de-correlating fiber in the transmitter. After orthogonal polarization conversion, optical carrier in y-pol merges with dual-polarized signals are detected via the same reception processes in the x-pol path. In compare to the single-pol scheme, there is no addition modifications for the proposed PDM-OFDM MFH at the RRU-side, which enables a high compatibility with single-polarized OFDM RoF systems and serves as a promising candidate of upgrading solution with a miniature capital cost increase of passive components in the remote node. It is worth bearing in mind that due to about 20-dB inherent polarization cross-leakage of PBS and PBC, we must use an optical coupler to combine two PDM signal in the transmitter. The received bit-error-rate (BER) performance versus different residual carrier power ratio which defined as Px/Py is also inset in Fig. 3. The received performance is uniform when the residual carrier power ratio is less than 25dB, while it goes down to 20 dB, which is typically the polarization extinction ratio of PBS and PBC, there is about a 1-dB performance degradation. As the residual carrier power ratio equal 15 or 10 dB, it would cost around 2.2- or 8-dB power penalty at the FEC threshold of BER=3.8e^{-3}.

III. Experimental Results

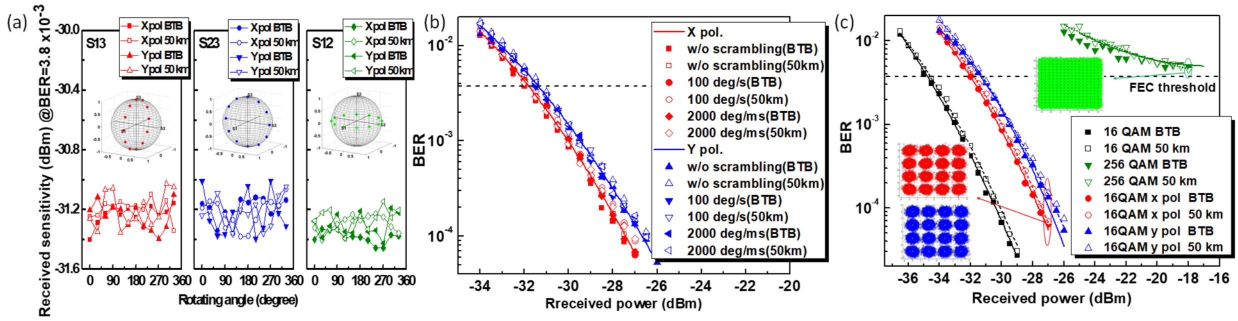

Fig. 4 (a) Received sensitivity versus rotating angle with 3 traces. (b) Received performance with different SOP scrambling rates. (c) Received BER performance at CSPR=1 dB and launched power equals to 1dBm.

Figure 4(a) shows the received sensitivity versus the input angles of the feeder fiber. The corresponding angle points on Poincaré sphere are also inset in Fig. 4(a), which are circled around S1/S3, S2/S3 and S1/S2 plane, respectively. The rotating angle began from the origin of S1, S2, and S1 axis in these measurements. It is worth to note that since the SOP is directly measured by the PS, it is a combined SOP of dual-pol signals and optical carrier. As expected, the performance is quite stable for both x- and y-pol signals of all scenarios and only about 0.4-, 0.4- and 0.3-dB sensitivity deviations among rotating angles are measured in these 3 traces. To further investigate the robustness of the proposed scheme against the SOP changing, we randomly scramble the input signal's SOP with different scrambling rate (S.R.). Figure 4(b) shows the average BER performance of S.R.=0 deg/s, 100 deg/s, and 2000 deg/ms. The proposed scheme shows high tolerance of SOP changing and its performance of each S.R. scenario are highly uniform. The received sensitivities are -32 dBm and -31.5 dBm for x-pol and y-pol signals, respectively. A 0.5-dB sensitivity degradation in y-pol signal is observed because CSPR value is reduced because the FBG induces power loss in the carrier's SOP rotating path. Figure 4(c) exhibits the BER versus received power with single-pol 16- and 256-QAM and dual-pol 16-QAM, which carriers about 29.6-, 59.2- and 59.2-Gb/s data rate, in both BTB and 50-km cases. The power penalty between BTB scheme and after transmission is negligible. Compared to the single-pol 16-QAM scheme, the power penalty is around 3-dB. This can be attributed to the received power is uniformly distributed to each polarized signal. However, under the same channel capacity, single-pol 256-QAM cannot meet the specified FEC threshold, whereas our proposed PDM scheme can achieve 33-dBm and 32.5-dBm power budget for x- and y-pol signals with 1-dBm launched power

IV. Conclusions

The proposed passive PDM de-multiplexing OFDM scheme is an attractive and cost-effective method to double the channel capacity and provide wide-area of coverage for A-RoF based MFH without any modifications at the RRU-side. An aggregate data rate of 59.2-Gb/s is achieved over 50-km SMF transmission with widely available SOP input range and high SOP changing tolerance of 2,000 deg/ms.

V. References

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