Polarization-Tracking-Free PDM Supporting Hybrid Digital-Analog Transport for Fixed-Mobile Systems

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***Abstract*—For fixed services such as hybrid fiber-coaxial (HFC) and passive optical network (PON) with deployed fiber networks, it is desirable to exploit the potentials to support wireless services in fifth-generation (5G) mobile data communications on top of the existing fixed networks. We propose a polarization-division multiplexing (PDM) scheme to achieve co-delivery of independent signals for fixed-mobile convergence. This is achieved by removing unwanted optical carrier in each polarization, thus the proposed system can resolve the polarization-tracking issue in conventional PDM. It has been demonstrated in this letter that the polarization-tracking-free PDM system can support co-transmission of respective 70-Gbps digital and analog signals over 20-km single mode fiber. Experimental results have shown low crosstalk between two polarizations. The proposed PDM system is compatible with wavelength-division-multiplexing (WDM) network and is capable of enhancing the spectral efficiency of WDM channels. The inherent single-sideband feature of the proposed PDM also enhances long-range services.**

***Index Terms*—Polarization division multiplexing, polarization-tracking free, hybrid digital-analog transmission, fixed-mobile convergence.**

I. Introduction

Large global business investments are anticipated for the deployment of fifth-generation (5G) network infrastructure. On the other hand, there is heavy ongoing research and development to improve system capacity and flexible architectures for various fixed access networks. In order to facilitate 5G deployment and maximize the capability of fixed networks, it is desirable to achieve efficient unification of the fixed and mobile network [1], [2]. Many attempts have been made to drive fixed-mobile convergence. In [3], mobile fronthaul over wavelength-division-multiplexing passive optical network (WDM-PON) was introduced for 5G low-latency service. 63% of all mobile traffic has already been offloaded through Wi-Fi routers supported by hybrid fiber-coaxial (HFC) [4]. One of the main challenges for HFC-mobile convergence is the latency limitation based on data-over-cable service interface specification (DOCSIS) in the HFC network. Recently, CableLabs and Cisco have demonstrated low-latency Long-Term Evolution (LTE) over DOCSIS using commercial platforms [5]. These methods are important initiatives of mobile service over fixed networks, but most of them require interface design between two systems. Consequently, sharing the fiber infrastructure as well as delivering fixed and mobile services independently becomes a desirable solution to avoid the complexity, latency, and bandwidth limitations in the interface design.

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To share the fiber infrastructure, it is important to minimize influence of the additional 5G service on the existing service, e.g. the spectral efficiency. Instead of sharing the capacity, discovering unoccupied dimensions is one efficient way to achieve this goal. Utilizing the orthogonal polarizations is one of the promising solutions, which potentially doubles the spectral efficiency. However, polarization-orthogonal lights, polarization-tracking techniques and digital signal processing (DSP) are required for conventional polarization-division multiplexing (PDM) [6]–[8], most of which are complicated and impractical for fixed access networks.

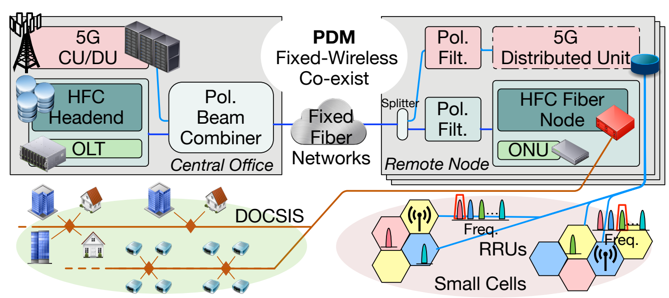

Fig. 1. 5G overlay over fixed networks supported by the proposed PDM for fixed-mobile convergence.

We propose a polarization-tracking-free PDM to overlay 5G over fixed fiber networks for fixed-mobile convergence, as shown in Fig. 1. The polarization-tracking-free PDM demultiplexing is achieved by removing the optical carrier of the opposite polarization state, which can be achieved with an optical filter instead of complicated DSP. This convergence system based on the proposed PDM scheme requires the same communication spectrum occupancy as the original fixed network. Therefore, it can be effectively scaled up to a WDM network which is widely deployed in current fixed access networks. In this letter, co-delivery of hybrid digital-analog signals for fixed and mobile services is experimentally demonstrated by utilizing the proposed PDM scheme. Respective 70-Gbps digital and 73.44-Gbps analog signals are transmitted through two orthogonal polarizations over 20-km standard single mode fiber (SSMF) within optical bandwidth of 33

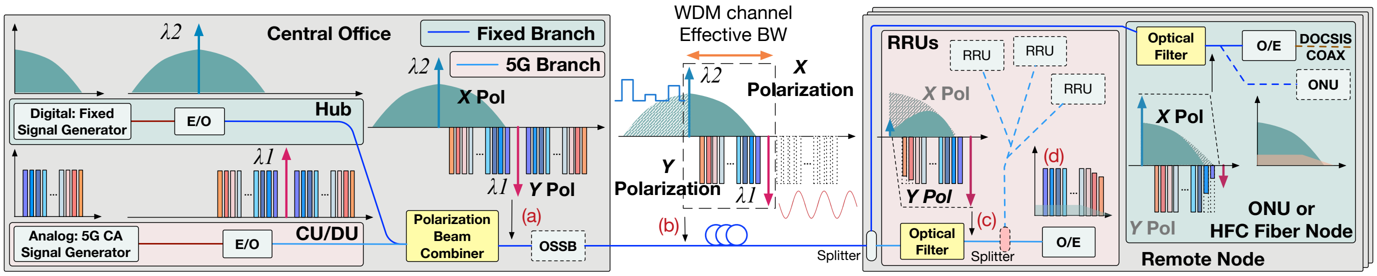

Fig. 2. Schematic diagram and operating principles of the proposed polarization-tracking-free PDM system.

GHz, meeting the capacity requirements of both 5G and most fixed access networks. Crosstalk is also investigated in the proof-of-concept experiment. Experimental results have shown low interference between two polarizations.

II. Operating Principles

The operating principles of the proposed polarization-tracking-free PDM system are illustrated in Fig. 2. Two lasers generate the optical carriers for 5G and fixed networks. The spectrum encompassed by two optical carriers is the effective bandwidth of the PDM system, as shown at Fig. 2, point (b). Two optical signals are combined and aligned to two orthogonal polarizations through a polarization beam combiner (PBC). Frequency overlap exists between two optical signals owing to PDM. After the PBC, optical single sideband (OSSB) can be applied to filter out the redundant sidebands. Here OSSB can be achieved by a tailored optical filter or simply by the bandwidth confined by one WDM channel.

In conventional PDM systems, complicated DSP is required to separate two polarizations. However, in the proposed system only the desired optical signal is reserved and extracted after photo-detection, by suppressing the optical carrier on the opposite polarization. For example, the optical carrier of the fixed branch is filtered out to extract the 5G signal. Losing the major part of the optical carrier, the residual optical signal of the fixed branch only outputs weak noise-like electrical signal at the photodetector (PD) as indicated by Fig. 2, point (c) and (d). It is worth noting that the power of such noise-like electrical signal is proportional to the residual power of its filtered optical carrier. With an appropriate small guard band, the proposed tracking-free design can relax the alignment accuracy of the optical filtering and still provide high isolation for PDM demultiplexing. The trade-off exists between the width of the guard band and wavelength alignment. As the wavelength of the optical filter deviates, the guard band is supposed to be widened to avoid failure in PDM demultiplexing, which can be quantified by signal-to-interference ratio (SIR), the power ratio between the desired signal and the interference from the undesired signal. The width of guard band is jointly dependent on the steepness of the optical filter and the alignment accuracy. Assume frequency difference of Δf_1 is needed for the given roll-off of the optical filter to achieve the carrier suppression associated with the targeted SIR, and the allowed frequency misalignment is $\pm\Delta f_2$, then the guard band should be larger than $\Delta f_1 + 2 \times \Delta f_2$. In the experiment, more than 20 dB suppression of the opposite optical carrier can be obtained, meaning that the SIR of the desired electrical signal can achieve more than 20 dB. As a result, the system can separate two polarizations with satisfying SIR without complicated polarization tracking.

One of our previous work using a polarization-tracking-free receiver for PDM signals can be seen in [9]. In this letter, co-transmission of high-speed digital and analog signals for fixed-mobile convergence is demonstrated. For the fixed networks, the modulation formats between central office (headend in HFC, optical line terminal, OLT in PON) and remote nodes (fiber node in HFC, optical network unit, ONU in PON) are usually digital modulations such as on-off keying (OOK), pulse amplitude modulation (PAM), and differential phase shift keying (DPSK) [10]. In the proof-of-concept experiment, without losing generality PAM4 is applied for the fixed branch. For the 5G branch, the PDM system serves as the link fronthaul I (FH I) between the central unit (CU)/distributed unit (DU) and remote radio units (RRUs) defined in Next-Generation Fronthaul Interfaces (NGFI) [11], [12]. For the link between CU/DU and RRUs, both digital-radio-over-fiber (D-RoF) and analog-RoF (A-RoF) can be utilized [13]. In our experiment, A-RoF orthogonal frequency-division multiplexing (OFDM) is employed. It is worth noting that the modulation formats on both polarization states are independent. However, the hybrid digital and analog transmissions employed in this experiment significantly exemplify the capability of the proposed PDM system. In the experiment, in order to focus on the fiber infrastructure sharing achieved by the proposed polarization-tracking-free PDM scheme, transmissions of both the fixed and 5G branches terminate at the remote nodes. Further delivering of the 5G branch optical signal to each RRUs and their spectrum assignment will not be discussed here.

III. Experimental Set-up

The experimental set-up is shown in Fig. 3. The wavelengths of two external-cavity lasers (ECLs) are 1548.978 nm (ECL1) and 1548.720 nm (ECL2) for the 5G and fixed network, respectively, encompassing effective bandwidth of 33 GHz. The electrical digital and analog signals are modulated to the optical carriers through two Mach-Zehnder modulators (MZMs). The optical filtering mentioned in Section II to obtain single-sideband signals is skipped in this experiment due to the insufficiency of available optical filters. Instead, the optical filters in the receiver which are used to reject opposite optical carriers for PDM demultiplexing will take over this duty and inherently achieve the OSSB operations. This modification will not significantly impair the performance of the overall system. The spectrum of two light sources carrying signals is plotted in Fig. 3(a). Fig. 3(b) gives an example spectrum when the optical filter in the transmitter is applied and out-of-band sidebands are filtered out, providing a clean spectrum within the PDM channel. After the PBC, the hybrid optical signal is transmitted over 20-km SSMF. At the receiver, i.e. the remote node, the hybrid optical signal is first amplified by an Erbium doped fiber amplifier (EDFA) and then split into two branches. In each branch, an optical interleaver functioning as an optical bandstop filter passes the hybrid PDM signal, with its notch aligned to the wavelength of the opposite optical carrier. The spectra of the filtered optical signals are plotted in Fig. 3(c) and (d). Optical-carrier suppressions can achieve 30 dB and 20 dB in the 5G and the fixed branches, respectively. A PIN PD (u2t XPDV2120) with 50-GHz bandwidth is used to detect the optical signal and the output electrical signal is captured by an oscilloscope for offline DSP and analysis.

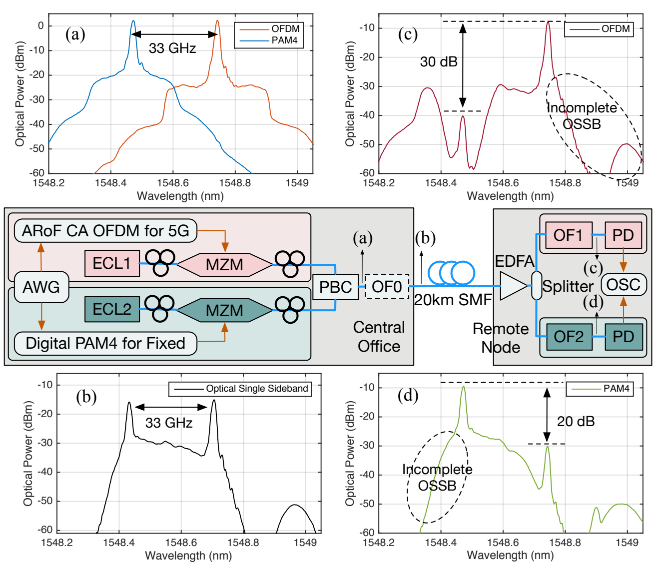

Fig. 3. Experimental set-up and spectra at the corresponding points. (OF: optical filter; PD: PIN photodetector; OSC: oscilloscope.)

In the 5G/analog branch, carrier-aggregation (CA) OFDM signal is transmitted. The multiband OFDM signal consisting of 34 bands spans from 400 MHz to 20.8 GHz. The subcarrier spacing is 30 MHz. Each band has 18 payload subcarriers and the guard band comprises 2 subcarriers. The modulation format of each subcarrier is 16 quadrature amplitude modulation (16QAM), hence the data rate of the OFDM signal is 73.44 Gbps. Frequency-domain one-tap zero-forcing (ZF) equalization is applied in the OFDM demodulator after Fast-Fourier Transform (FFT) and cyclic prefix removal to recover the signal. In the fixed/digital branch, PAM4 signal is transmitted. The baud rate of the PAM4 signal is 35 GBaud, providing a data rate of 70 Gbps. Nyquist filtering is used to pulse-shape the PAM4 symbol, with the PAM4 signal occupying 17.5-GHz electrical bandwidth. Minimum-mean-square-error (MMSE) equalizer is used in the PAM4 receiver to recover the signal. Both the OFDM and PAM4 signals are generated by an arbitrary waveform generator (AWG, Keysight, M8195A) with 20-GHz physical bandwidth, and captured by an oscilloscope (Keysight, DSOZ254A) with 25-GHz physical bandwidth. It is worth noting that it is the limited bandwidth of AWG that constrains the overall data rate. With a wider available bandwidth of AWG and oscilloscope, the overlap of two polarizations would be wider and higher data rate can be delivered by the PDM system. In the experiment, the sampling rate of AWG is 60 GSa/s, the sampling rate of the oscilloscope is 80 GSa/s. The received signal is first down-sampled and then down-converted (only for the 5G branch) to the baseband. For both fixed and mobile signals, Volterra equalizaton is applied before other equalization process to mitigate the non-linearity.

IV. Experimental Results

In the experiment, bit-error rate (BER) versus the received optical power (ROP) of the PDM system is measured for both branches. The transmission scenarios with and without 20-km SSMF and the multiplexing scenarios with and without PDM for each branch are measured. For the scenario without PDM, all set-ups remain the same as that with PDM except that the opposite polarization is disconnected from the PBC. Furthermore, the crosstalk between polarizations is also investigated. In the crosstalk measurement, the ROP of the desired optical power is fixed and the optical power of the other branch is varied.

For the digital/fixed branch, 70-Gbps data rate is achieved over 20-km SSMF. The power spectral density (PSD) of the PAM4 signal retrieved by the oscilloscope is shown in Fig. 4(a). From Fig. 4(b), BER of the fixed branch achieve below the forward-error-correction (FEC) threshold after 20-km SSMF. For 20-km SSMF scenario, the receiver sensitivity is around 1 dBm, which can be improved by using PD with the transimpedance amplifier (TIA) or an avalanche photodiode (APD). Compared to the results in the back-to-back (B2B) transmission, there is 4-dB penalty of sensitivity, mainly due to the incomplete OSSB filtering during the polarization demultiplexing process shown in Fig. 3(d). On the other hand, the BER performance of the digital branch with and without PDM is shown in Fig. 4(c). It can be seen that PDM has induced 4-dB sensitivity penalty. This penalty mainly results from the residuals of the opposite polarization, which not only shares the EDFA gain and ROP quota but also induces the noise-like beating signal. To investigate the crosstalk, Fig. 4(d) plots the influence of the analog branch to the digital branch on BER. It can be seen that the BER variation of the digital branch is less than one order of magnitude when ROF of analog branch varies from 4.5 dBm to -8.5 dBm, proving the stability of the proposed PDM system.

For the analog/5G branch, data rate of 73.44 Gbps is achieved. The PSD of the 5G CA OFDM signal captured by the oscilloscope is shown in Fig. 4(e). For the OFDM signal, BER of channel 2, 19, 34 (CH2, 19 and 34) are selected for illustration without losing generality. The BER of inner bands

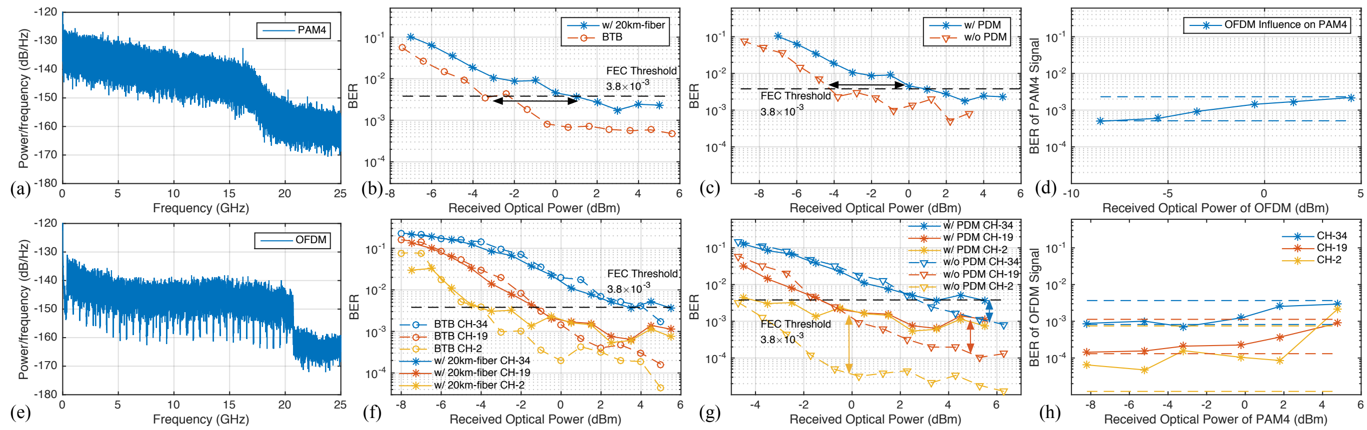

Fig. 4. PSD of (a) PAM4 and (e) OFDM. BER vs. ROP for PAM4 branch: (b) With and without 20-km SSMF; (c) With and without PDM; (d) Crosstalk. BER vs. ROP for OFDM branch: (f) With and without 20-km SSMF; (g) With and without PDM; (h) Crosstalk.

(CH2) is better than that of outer bands (CH34) due to the frequency response of the electrical equipment. The penalty due to fiber transmission is more prominent for inner bands as shown in Fig. 4(f), as the outer bands suffer more from low signal-to-noise ratio hence penalty due to fiber transmission is less significant in comparison. The other reason is signal-signal beating interference (SSBI) induced by incomplete OSSB. Similarly, when comparing the BER with and without PDM, inner bands present greater penalty caused by PDM as shown in Fig. 4(g). In the investigation of the influence of the digital branch to the analog branch, it can be seen from Fig. 4(h) that the BER of each channel varies within one order of magnitude except for the extreme case, given the ROP of the digital branch fluctuating over 13 dB (-8.2 dBm to 4.8 dBm).

V. Conclusion

In this letter, we have proposed a polarization-tracking-free PDM system that can support fixed-mobile convergence integrated with WDM architecture. In comparison with a regular non-PDM system, the additional devices needed to implement the proposed PDM system are mainly passive devices such as PBC and optical filters, yet sucessfully by-passing the complicated polarization-tracking DSP required in conventional PDM systems. These devices are added in the central office and remote nodes requiring no changes in the fiber access networks, avoiding the high cost to pull extra fiber. The proposed PDM system is spectrum-efficient and WDM-compatible. It has been demonstrated in this letter that the proposed polarization-tracking-free PDM system is capable of supporting the co-transmission of digital and analog signals, providing 70-Gbps data rate over 20-km SSMF for each polarization. Regarding the crosstalk issue, it has been shown that the BER variation of one polarization can maintain within one order of magnitude with the optical power of the opposite polarization changing over 13 dB ROP, proving the desirable and stable operation of the system. The proposed polarization-tracking-free PDM system is a promising candidate to provide 5G overlay onto fixed fiber networks, achieving fixed-mobile convergence.

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