Single Photodiode-per-Polarization Receiver for 400G Systems

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Abstract: We present a simplified heterodyne receiver using one single ended photodiode per polarization for polarization multiplexed coherent signals. We demonstrate this receiver for the reception of PM-16QAM over field-installed metro-area fibers at distances up to 306-km.
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1. Introduction

Systems using single-ended photodiodes at the receiver-side have recently regained interest for application in short-haul metropolitan-area and data center interconnect networks [1,2], in an attempt to simplify receiver architecture while allowing for high spectral efficiency. Several high-capacity demonstrations have used a residual optical carrier to allow QAM signaling and dispersion compensation, while overcoming signal-signal beat interference (SSBI) through various digital signal processing approaches (DSP) [1-4]. However, these techniques require significant modification to transmitter- or receiver-side DSP, and often increase computational complexity, which may lead to penalties in power consumption, cost and processing latency.

An alternative technique is to suppress SSBI by increasing the optical carrier-to-signal power ratio (CSPR). If the carrier is transmitted with the signal, this can lead to a large sensitivity or required OSNR penalty. However, if the optical carrier is provided at the receiver by a local oscillator (LO) laser, the receiver-side CSPR can be large without incurring performance penalties. LOs are commonly used in intradyne coherent reception, though the required precision optical hybrids and balanced photodiode pairs have hindered adoption in cost-sensitive applications.

Here we use a simplified heterodyne detection front-end, requiring only a standard 3dB optical coupler and a single photodiode. This arrangement significantly reduces the complexity of the optical componentry, requires a single ADC per polarization, and uses the same DSP blocks as an intradyne system. We demonstrate transmission of PM-16QAM at 60-62 Gbd over installed metro-area fiber up to 306 km. Moreover, back-to-back measurements indicate greater sensitivity than state-of-the-art single photodiode techniques [1,2]. This shows that complicated SSBI cancellation DSP can be traded for an off-the-shelf laser and fiber couplers for single photodiode coherent reception.

2. Concept and Experiment

Heterodyne reception systems have been used in optical systems for decades (e.g. [5]), and recently to simplify coherent receivers [6]. Here we propose using a strong LO to further simplify the receiver by removing the need for path-length-matched optical couplers (as opposed to [6]). For each received polarization, a signal and LO are passed into the input ports of a 3dB coupler, with one output port connected to a single photodiode, as shown in Fig. 1.

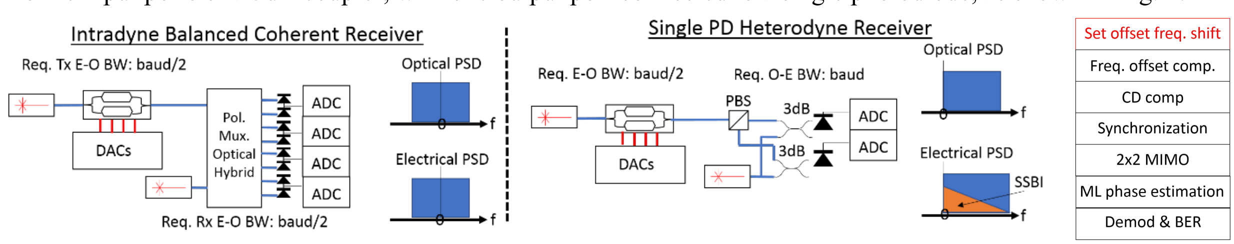

Fig. 1: Basic architecture of (left) intradyne and (middle) single photodiode heterodyne receivers. The insets compare the received power spectral densities (PSDs) of the optical and electrical signals. (right) Receiver DSP flow for the intradyne and heterodyne systems. These are identical, excepting the frequency shift stage at the start of the heterodyne Rx DSP (red).

If a Nyquist-shaped signal is received, the LO and signal need to be detuned by just over half the signal's symbol rate. The resultant detected signal is then mixed down by this frequency detuning to base-band, which allows standard intradyne DSP blocks to be used to extract the signal data (Fig. 1, right). In comparison to intradyne systems, this system requires a quarter of the number of photodiodes, half the number of ADCs, and does not require precise path lengths in either the optical or electrical domains. However, the electrical bandwidths of the photodiode and ADC need to be doubled, as is the case with other single-photodiode systems [1-4].

The experimental set-up is shown in Fig. 2. A compact, 30-GHz bandwidth InP dual-polarization complex Mach-Zehnder modulator (DP-MZM) is driven by a 90-GSa/s arbitrary waveform generator (AWG), to modulate light from a 100-kHz linewidth external cavity laser (ECL). The drive signals are pre-emphasized to provide a flat power response out of the modulator as measured by a 100-MHz resolution optical spectrum analyzer, and shaped with a 10% roll-off RRC filter. Since a single polarization received by the intradyne system occupies both 160GSa/s input ports on the scope, we are only able to measure a single polarization, and so only send a single polarization signal, to avoid penalties from polarization cross-talk and ensure a fair comparison. The 16-QAM signal is then either noise loaded or transmitted through an EDFA-amplified field-installed fiber link. At the receiver side, we used either a single-polarization intradyne receiver based on a 90^o optical hybrid and two individual balanced photodiode pairs, or a dual-polarization heterodyne receiver using a single 3-dB coupler and single photodiode per polarization. The intradyne receiver was manually de-skewed to below 500 fs. Note that for the heterodyne receiver, each path between optical components used as-is pigtails on separate device – i.e. no de-skew was applied. A 100-GHz passband filter was used before the receiver to reduce out-of-band ASE noise. The peak-to-peak amplitude of the waveform measured by the oscilloscope was similar for both types of receiver.

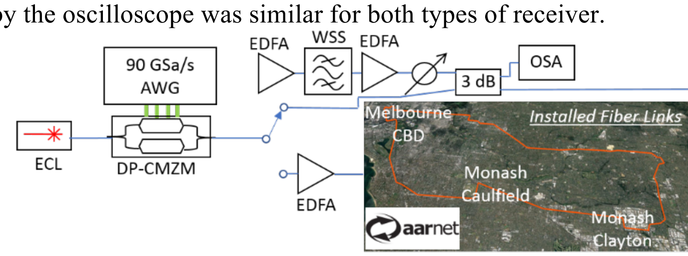

Fig. 2: Experimental set-up for the single photodiode-per-polarization receiver trials. EDFA: erbium doped fiber amplifier, OSA: optical spectrum analyzer, WSS: wavelength selective switch, (PM) 3dB: (polarization maintaining) 3 dB coupler.

Fig. 3 shows the performance of both intradyne and heterodyne receivers against noise loading. An OSNR penalty of about 3 dB penalty was measured when using the heterodyne receiver, compared to the intradyne system, near an indicative 20% soft-decision FEC limit at BER=2.2×10^{-2}. This penalty is expected at low OSNRs, where the signal-noise beat is dominant, as LO-ASE beat noise either side of the LO is folded into the measured signal band. We also note that the error floor for the heterodyne system is higher than the intradyne system, as the wide bandwidth reception required for the heterodyne systems intrinsically introduces more noise. This error floor also increases as the symbol rate is raised from 60 Gbd to 62 Gbd, as the 62.5-GHz cut-off anti-aliasing filter in the oscilloscope attenuates high-frequency signal components.

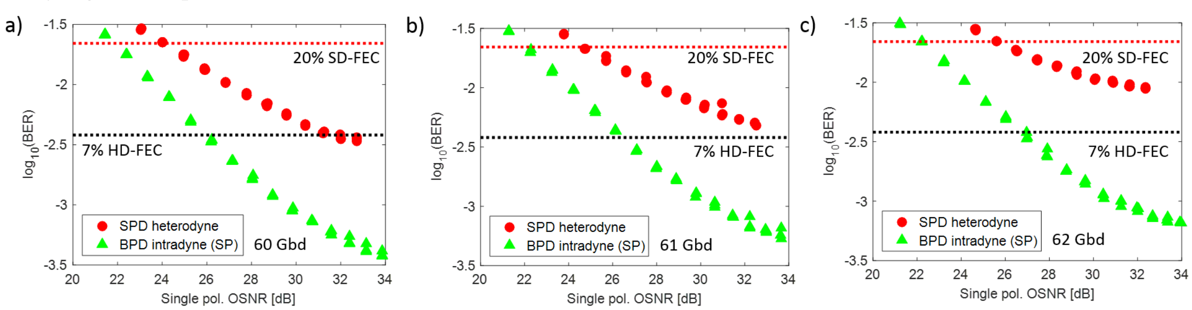

Fig. 3: Back-to-back performance results, with signals modulated at a) 60, b) 61 and c) 62 Gbd. Red circles are for dual-polarization measurement with the heterodyne receiver, green triangles for single-polarization intradyne reception. Indicative thresholds for a 7% HD FEC and 20% SD FEC are shown in dotted lines.

We then tested the signals after transmission through a metro-area field-trial system. Fig. 4 shows the BER for all the symbol rates after transmission over various distances. The optimal signal launch power for all systems was measured to be 6 dBm. The 23.8, 47.6 and 76.5 km distances are single spans, while the 306 km link uses four spans of 76.5 km. The single spans have 7-, 15- and 21-dB loss for 23.8, 27.6 and 76.5 km distances, respectively. The 306 km link comprised two spans with 21 dB loss and two of 23 dB loss. The received OSNRs were 29.2, 28.6, 27.0 and 21.5 dB for 23.8, 47.6, 76.5 and 306 km, respectively. For the heterodyne system, the 20% SD-FEC limit was cleared for each case except for 62 Gbd over 306 km, allowing for transmission of up to 412 Gb/s over single spans (maximum tested distance of 76.5km / 21.5 dB loss), and 407 Gb/s over 306 km, discounting OTN overheads. We note that for the single-span cases, the measured BER is well below the SD-FEC limit, and so an alternate high-rate hard-decision FEC code may be preferable in terms of latency. The expected superior performance of the intradyne system allows it to clear the 7% hard FEC limit of BER=3.8×10^{-3}, increasing the aggregate rate to above 460 Gb/s (assuming PM operation).

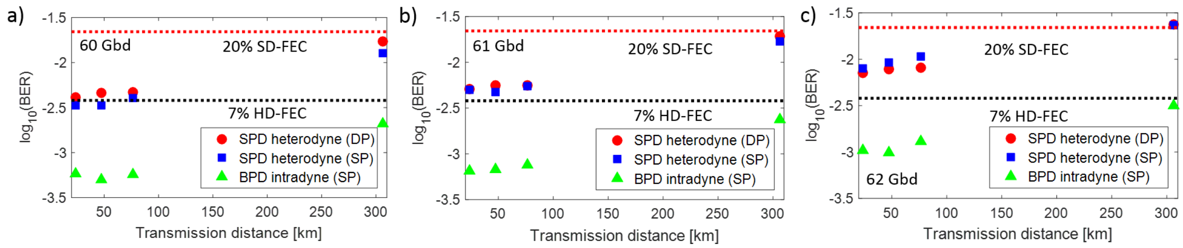

Fig. 4: Transmission performance at optimum launch power (6 dBm) over various distances of field-installed fiber with a) 60, b) 61 and c) 62 Gbd signals received. Red circles represent dual-polarization heterodyne reception, blue squares for heterodyne reception of a single polarization signal, and green triangles intradyne reception of a single polarization signal. Indicative HD and SD FEC thresholds are shown in dotted lines.

3. Discussion

Comparing the single photodiode heterodyne receiver results to state-of-the-art single photodiode Kramers-Kronig receivers, the back-to-back BER achieved here is comparable to the 64-GBd 16-QAM system in [2], and the required OSNRs at a BER near 1×10^{-2} are at least 5-dB better than shown for the 60 and 64 Gbd KK receivers [1,2]. The receiver bandwidth required here is comparable to those systems. Additionally, the required DSP at both the transmitter and at the heterodyne receiver is very similar to many 400G channel demonstrations using intradyne receivers, which may be an advantage when considering transceiver design.

We note that the inclusion of a LO in the receiver is often dismissed for short-reach systems. However, we show here that the addition of a commercial laser package may provide benefits over the inclusion of new and complicated digital processing blocks in future high-rate, single-photodiode receivers. Further, an LO is said to be required in order to use polarization multiplexing to effectively double the spectral efficiency of single photodiode systems [7]. We also note that the intradyne system significantly outperforms the heterodyne system, so may be preferred if the costs of the hybrid-plus-balanced PD front-end can be reduced. Moreover, an intradyne system would require only half of the E-O conversion bandwidth of single-photodiode systems, which may prove critical if systems are limited by available E-O (i.e. PD and ADC) bandwidths. However, as state-of-the-art, commercially available DP-MZMs have significantly lower bandwidths than commercial photodiodes, a much higher bandwidth is currently achievable for the receiver than for the transmitter.

Moreover, the heterodyne system shown here does not require the transmission of an optical carrier along with the signal, making this receiver compatible with the signals most often investigated (and deployed) in long-haul transmission systems. Additionally, the receiver DSP flow very similar to intradyne DSP, with only a downshifting mixing stage required before processing. As such, the receiver we demonstrate here would seem to provide a simplified optical front-end design, able to leverage the DSP ASICs and transmitters designed for intradyne systems.

4. Conclusion

We have demonstrated a single photodiode-per-polarization receiver based on a simplified heterodyne receiver. By using off-the-shelf power splitters and an external cavity laser, we achieve heterodyne detection of 400 Gb/s class signals. We have transmitted a >400 Gb/s signal over 306 km of installed metropolitan area fiber to show the feasibility of systems using this receiver for metro/regional networks or data center interconnections. This demonstrates shows the ability to trade off complicated SSBI cancellation DSP for a heterodyne optical receiver front-end in single-photodiode receivers.

Acknowledgements

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