Simplified Coherent Receivers for Passive Optical Networks

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Abstract *Simplified coherent receivers are attractive for future high-speed passive optical networks (PON) since they enable a trade-off between performance and cost. We present the most promising solutions for 200 Gb/s, demonstrating that single polarisation heterodyne receivers achieve the PON requirements at significantly reduced cost.*

Introduction

Bandwidth demand continues to increase exponentially, and the trend is forecast to continue, largely driven by future 6G deployment, as well as cloud based services[1]. These effects show the need for increased datarate in future access networks. As the International Telecommunication Union-Telecommunications Standardization Sector (ITU-T) has standardised Higher Speed PON[2],[3] at 50 Gb/s, and has started to work on Very High Speed PON[4], aiming for operation beyond 50 Gb/s/λ. Studying trends from previous standards by both IEEE and ITU-T, it is likely that a four-fold increase in capacity will be the target, as smaller increases may not entice industry members to invest in the technology. As such 200 Gb/s PON is a focus in the research community[5].

There are multiple approaches, that are proposed to achieve 200 Gb/s. It is clear, that the traditional approach of intensity modulation / direct detection (IM/DD) coupled with non-return-to-zero signalling is unlikely to meet the power budget requirements[5],[6]. Demonstration of IM/DD PON for 200 Gb/s line rate exist, however use PAM-4 or higher modulation[7],[8] format to increase spectral efficiency and are only able to meet power budget requirements using extensive DSP[9] and using Raman amplifiers[10].

On the other hand, coherent technology has been proven at capacities significantly higher than 200 Gb/s even in PON applications[11], however the cost of coherent transmitters and receivers are magnitudes higher than using IM/DD[1]. As a consequence, simplified coherent receivers have re-emerged as a research interest.

PON application differs from metro and core networks in multiple ways, and these differences govern the technology requirement for access networks. The point to multipoint nature creates a unique asymmetry of the system. The connection to the core network at the optical line terminal (OLT) and the end nodes at the optical network unit (ONU) have different cost requirements. The costs of the OLT are shared between all users, and as such higher degree of complexity in both component choice and DSP are allowed, compared to the ONU where costs are kept to the minimum. This leads to the research interest in low cost coherent receivers to be implemented at the ONU. These requirements, coupled with short reach (20 km) and high power budget ($>$ 29 dB), due to the passive splitters in the network create unique challenges for future PON.

In this paper we introduce the main ideas of simplified coherent receivers, focusing on their use in 200 Gb/s/λ or faster line rate downstream applications for future PON.

Simplified Coherent Receivers

An understanding of the conventional phase and polarisation diverse coherent receiver is needed in order to understand the ideas behind simplified coherent receivers and their use cases. This receiver has been used extensively in core and metro applications, and offers phase- and polarisation-diversity over IM/DD solutions, significantly enhancing spectral efficiency. For polarisation demultiplexing a polarisation beam splitted (PBS) is used. To achieve phase-detection, a local oscillator (LO) laser is needed, along with 90° hybrids on both polarisations, and finally the detection is realised by four balanced photodiode pairs, as shown in fig. 1a.

Simplified coherent receivers were first proposed at the birth of coherent technology, when the constraints on computational power available limited the DSP capabilities of the technology. As such non-DSP based techniques for polarisation tracking were investigated. Proposals using a single polarisation receiver with separate polarisation tracking[12], or transmitting redundant

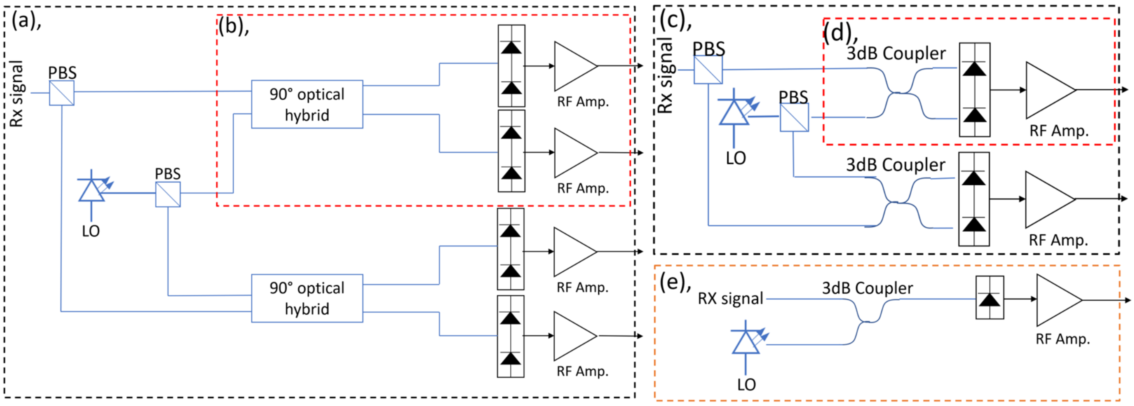

Fig. 1: Coherent receiver architectures. (a): Full coherent receiver (b): Single polarisation intradyne receiver (c): Polarisation diverse heterodyne receiver (d): Single polarisation heterodyne receiver (e): Minimal coherent receiver

information on both polarisations using polarisation scrambling[13] were among the early proposals. These proposals were discarded in favour of the full coherent receiver enabling polarisation diversity and using DSP for polarisation tracking. However, the idea of simplified coherent receivers have re-emerged in the PON field, as here cost is key, and steps that can reduce both the number of analogue components and DSP power consumptions show the viability of coherent PON.

There are two key techniques for reducing complexity. Firstly, eliminating polarisation diversity, secondly moving to heterodyne detection. Alongside the previously mentioned techniques, the use of Alamouti-coding[14], a space-time block code, have emerged as solutions for polarisation insensitive techniques. Both polarisation scrambling have the advantage that it is applied at the transmitter, which is ideal for a downstream PON scenario. The viability of Alamouti coding has been shown for higher speed PON and faster applications[15] using a modified DSP specific to this code[16]. Recently a third technique based on differential group delay (DGD) has also been proposed[17]. These types of transmission allow the receiver to be simplified as shown in fig. 1b.

The second way of reducing the number of opto-electronic component is moving from intradyne detection to heterodyne. This doubles the bandwidth requirement of the photodiodes and TIAs, however, effectively halves the component number, by moving the baseband conversion into the RF or the digital domain. Since bandwidth scales sub-linearly with cost, this is an appealing alternative, provided that the high-bandwidth components exists. This receiver is shown in fig. 1c. Combining the heterodyne detection with transmitter-side polarisation diversity, the receiver can be reduced to a single branch of the full coherent receiver, consisting solely of LO laser, a 3 dB coupler and a balanced photodiode, as shown in fig. 1d. Final simplification is using a single photodiode instead of the balanced pair, resulting in a minimal coherent receiver, as depicted in fig. 1e. A comparison of the optical and electrical component requirements is shown in table 1.

It is worth mentioning that simplified coherent receivers based on 3 x 3 couplers have also been explored in the past for PON applications[18], however these solutions require more IO ports than the above mentioned simplified receivers, and as such are not considered viable alternatives.

Performance of Simplified Receivers

Analysing the performance of the receivers requires an in-depth knowledge of the inherent penalties due to simplification. Moving to heterodyne detection introduces a doubling of the bandwidth requirement. This by itself does not introduce sensitivity penalties[19], however can increase costs.

Transmitting redundant information on both polarisations will however introduce a 3 dB sensitivity penalty, as only one polarisation is detected, and moving to the minimal coherent receiver introduces an additional 3 dB signal penalty[20]. These penalties are theoretical minimums and experimental work encounters other penalties that decrease the receiver sensitivity at the pre-FEC BER threshold.

Reducing the number of components at the ONU side is considered to be a priority in lowering the costs for coherent PON, Alamouti coding has been studied extensively for this purpose. Alamouti coding has no penalty due to the polarisation state, however there is a significant SNR penalty with increasing linewidth of both LO and transmission lasers[16]. At this point, choosing between the heterodyne and intradyne solutions for

Tab. 1: Comparison of component requirements of the coherent receivers. The number in the bracket indicates bandwidth requirement for 200 Gb/s assuming 16 QAM modulation. (Balanced Photodiode (BPD), Photodiode (PD), Transimpedance Amplifier (TIA), Analog-to-Digital converter (ADC))

	Optical Components	Electrical Components
Dual Polarisation Intradyne	2 PBS, 2 90° hybrids, 4 BPDs (12.5 GHz)	4 TIAs (12.5 GHz), 4 ADCs (12.5 GHz)
Dual Polarisation Heterodyne	2 PBS, 2 3-dB couplers 2 BPDs (25 GHz)	2 TIAs (25 GHz), 2 ADCs (25 GHz)
Single Polarisation Intradyne	1 90° hybrid, 2 BPDs (25 GHz)	2 TIAs (25 GHz), 2 ADCs (25 GHz)
Single Polarisation Heterodyne	1 3-dB coupler, 1 BPD (50 GHz)	1 TIAs (50 GHz), 1 ADCs (50 GHz)
Minimal Coherent	1 3-dB coupler, 1 PD (50 GHz)	1 TIAs (50 GHz), 1 ADCs (50 GHz)

single polarisation is a key consideration. Heterodyne has higher bandwidth requirement, however halves the photodiode count and relies on a single and easy integrated 3 dB coupler, whereas for intradyne a 90° hybrid is needed, with higher insertion loss. Overall, it can be stated that heterodyne detection has no SNR penalty, provided that the bandwidth requirement can be met.[21].

Multiple demonstrations are presented for 200 Gb/s Alamouti coded heterodyne receiver[22]–[24]. These demonstrations show that the power budget requirements can be achieved using a balanced photodiode at the receiver. Excess signal processing, such as pre-distortion at the OLT can improve sensitivity, and as the cost is shared between all users, this may be beneficial. Compensating for transmitter based IQ and gain imbalance can improve the power budget by 0.9 dB[23], and additional 1 dB can be achieved by mitigating the fibre non-linear distortion[24], with reported power budgets of 35 dB. The system, albeit using digital subcarrier multiplexing, has been demonstrated in real time as well[25], showing progress towards commercial use.

The minimal coherent receiver however exhibits additional penalties in practice above the 3 dB theoretical limit. This receiver is particularly sensitive to RIN noise due to the lack of common mode noise cancellation present in the balanced photodiode system. As such the performance is significantly degraded, showing a 5.5 dB sensitivity penalty over the balanced photodiode based receiver[23]. Yet, this receiver still meets the N1 class power budget requirement for PON and can be a great choice for very low cost applications.

When considering the cost of the PON system, the DSP complexity should also be considered. For the ONU side this is particularly important both in terms of power consumption and ASIC cost. Traditionally, IM/DD systems in PON did not have DSP enabled to reduce costs, however Higher Speed PON has included DSP in the standard[3]. This area is another example where for high datarate applications coherent has an advantage. The IM/DD solutions previously presented use either an LMS equaliser with 640 taps[10] or a Volterra equaliser of 183 length[11]. For Alamouti coding, the DSP stack is similar to the full coherent receiver[16], however due to the short reach nature of the PON network, the chromatic dispersion compensation filter is significantly shorter, or alternatively can be integrated into the LMS equalizer. For 200 Gb/s application, using 50 GBaud transmission, as few as 20 filter taps are suitable for time domain recovery. Assuming a 2 x 2 MIMO configuration for the adaptive equaliser, this is a total of 80 filter taps.

Conclusions

We present multiple architectures for simplified coherent receivers for future PON networks. The most promising solution is the single polarisation, heterodyne receiver, either using balanced photodiode or single photodiode. Both meet the PON power budget requirements (E2 and N1 class respectively), and the decision between them depends on the requirements of the specific application, and whether the balanced photodiode can effectively be integrated into the device.

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