Recent Progress and Outlook for Coherent PON

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Abstract: Coherent receivers offer high data rates and reach for optical access but, due to their complexity, have proved resistant to implementation. Here, recent research in low-complexity coherent PON is reviewed, and promising future research directions are identified.

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1. Introduction

Direct detection has been the stalwart of optical access networks. It is a technology which, up until now, has shown the ability to scale receiver capability with user demand, with network standards based on this technology now approaching 100 Gb/s using a combination of time and wavelength division multiplexing (TWDM). However, despite their inherent simplicity, direct detection systems do suffer from several limitations. As passive optical networks (PON) move towards terabit/s aggregate data rates, these shortcomings may make the continued use of direct detection unattractive. Limitations include poor receiver sensitivity, power fading due to chromatic dispersion at high symbol rates and long transmission distances, bandwidth- and power-inefficient modulation, a wavelength-indiscriminate response and, consequently, the inherent network and/or transceiver complexity then required to enable wavelength multiplexing.

Although other receiver architectures exist (e.g., differential detection), the obvious challenger to direct detection is coherent reception; a technique now widely adopted for long haul optical communications [1]. The advantages of this technique for PONs include a high receiver sensitivity (which can be used to extend reach and split ratio), frequency selectivity (inherently enabling WDM without optical filters), highly bandwidth- and power-efficient advanced modulation formats, and linear detection [2]. The linear detection is a particular powerful feature of these receivers, as it enables channel impairment compensation after conversion of the received signal to the digital domain (e.g., digital chromatic dispersion post-compensation).

However, these advantages come at a greater financial cost, due to the high optical complexity of coherent receivers. For example, the phase- and polarization-diverse digital coherent receivers (Fig. 1) used in long haul networks require two polarization beam splitters (for polarization diversity), two 90° optical hybrids (for phase diversity), four balanced photodectors (one per degree of freedom in the optical signal), four analog-to-digital converters (ADC), and one local oscillator laser (LO). Compare this with a typical optical network unit (ONU) based on direct detection, which may include only a single photodetector and a laser for upstream transmission.

The renewed interest in coherent detection for PON has sparked a flurry of research activity, focussed on simplifying coherent receivers to the point where they could be cost-effective for optical access networks (typically assuming complexity as a proxy for cost) [3]. So, with the plethora of new, low complexity designs now on offer, how does the future look for coherent PON? The remainder of this paper reviews the key receiver architectures and experimental demonstrations in this area, and concludes by looking at the performance of a hypothetical coherent ONU, with complexity exactly equal to its direct detection counterpart.

Fig. 1. [left] A conventional polarization- and phase-diverse coherent receiver. [right] a direct detection ONU, which can be converted to a simplified, balanced, heterodyne, coherent ONU with the addition of the dashed paths.
2. Simplified coherent receiver architectures

What is a coherent receiver? At a fundamental level, coherent reception is simply a method which uses a local phase reference to extract phase information from a signal [1]. In the case of optical communications, this means that a local laser source (i.e., a LO) is mixed with the signal before detection. Because the LO will only coherently beat with signals with the same state of polarization, recent research has investigated polarization-insensitive architectures for PONs, which forgo the use of a 90° optical hybrid. These include: 3x3 coupler-based receivers with polarization decoherence [4, 5], OLT-side (optical line terminal) polarization scrambling methods [6, 7], polarization-summed dual-photodiode receivers [8], and OLT-side polarization-time block coding (i.e., Alamouti coding) [9,10]. Of these, only [7] and [9] have been combined with heterodyne detection to achieve single photodiode operation.

The minimum optical complexity for a coherent receiver requires to use a 3 dB coupler followed by a single-ended photodiode, as illustrated in Fig. 1. Cano et al. [7] have proposed an OLT-side polarization scrambling (PS) method in which every symbol is transmitted alternately in orthogonal polarization states. It is applied at the OLT, requiring a polarization modulator operating at twice the symbol rate to provide polarization switching. Similarly, an Alamouti heterodyne receiver with the same receiver architecture, detects a signal (OLT-side polarization-time block coded) independently of the LO state of polarization. Although these receivers come at the expense of 9 and 6 dB sensitivity penalties due to PS technique (sacrificing one polarization mode and one time slot and half-rate Alamouti coding combined with heterodyne detection), respectively, one of the approach’s key advantages is that, although not a standard technique, it allows the simultaneous use of an ONU laser both as source and LO laser, as demonstrated in recent transmission experiments over installed fiber links [11].

Some key demonstrations of low complexity coherent receivers include the first prototype Gb/s ONU using heterodyne detection [12] (2011), a field trial of a DSP-less and ADC-less 8 × 1.25 Gb/s real-time analog intradyne coherent receiver over 35 km of SSMF [13] (2017), and a demonstration of a simple 3x3 coupler-based coherent intradyne receiver, shown to be compatible with burst mode operation [14](2017), albeit without polarization insensitive operation, and a demonstration of a long-reach 8 × 10.7 and 21.4 Gb/s bidirectional coherent WDM-PON using the Alamouti heterodyne receiver over 108 km of installed SSMF fiber [11].

Finally, briefly diverting from low complexity receivers, it should be noted that high complexity receivers can also be cost-effective, if used efficiently. For example, in [15], an entire OLT was implemented using a single, high bandwidth, phase- and polarization-diverse coherent receiver to detect 32 × 10 Gb/s upstream WDM channels. Although the device complexity is undoubtedly high for the OLT, being able to average the device cost over 32 users may actually be economically feasible, raising an interesting cost-complexity trade-off.

3. Equal complexity: coherent versus direct detection

As noted previously, the minimum requirement for coherent detection is a laser (to act as LO), and a photodetector. Consider the direct detection ONU shown in Fig. 1, where an externally modulated laser (EML) has been used for
upstream transmission. This ONU can include the ultra-simplified coherent receiver with the addition of the dashed paths. It is immediately apparent that the coherent ONU requires no additional complexity. Such a receiver is hypothetical, but could be practically implemented using, for example, OLT-side polarization tracking, as explored in [16].

Recently, a direct detection receiver was proposed for 4-ary pulse amplitude modulation (PAM), which used combinatorial logic to extract the most- and least-significant bits of a 4PAM signal [17]. Interestingly, this effectively implements a two bit ADC. Therefore we can ask: how would the coherent ONU and direct detection ONU perform if using the same 2 bit ADC? To investigate this, we simulated a 12.5 Gbd (25 Gb/s) 4PAM signal (where the level spacing was optimised separately for coherent and direct detection schemes) shaped using a 5th order low pass Bessel filter (70% symbol rate 3 dB bandwidth). The signal was attenuated and received using a balanced PIN photodetector with a responsivity of 1.24 A/W and 300 K temperature, either directly or using a coherent heterodyne scheme, before being passed to an ADC. Finally, the signal was digitally down-converted and equalized using a multi-modulus algorithm equaliser [18], and the bit error ratio (BER) was estimated. The sensitivity at a BER of $4 \times 10^{-3}$ is shown in Fig. 2.

For high ADC resolutions, it is reasonable to assume that the distortion due to quantization can be treated as additive, Gaussian noise [19]. Note that the significant sensitivity penalty for ADC resolutions below 3 bits is due to the breakdown of this assumption where, in this regime, the signal and noise become highly correlated (as can be seen from the constellations, inset). For this proof of principle, we did not attempt to mitigate this nonlinear quantization-induced distortion, but it is clear to see that 2 bit operation could be easily improved by the use of, e.g., a lookup table for equalization. Interestingly, the coherent results outperform the direct detection results at all ADC resolutions by more than 18 dB, indicating that, even with equivalent complexity, coherent receivers can offer superior performance. For reference, we show the aforementioned experimental result recently reported including a comparable direct detection configuration with a 2 bit ADC, but using an avalanche photodiode at the receiver instead of a standard PIN [17]. Here, the receiver sensitivity was in excess of -23 dBm, but still more than 10 dB short of the low complexity coherent heterodyne receiver with a 2 bit ADC. This low-resolution ADC-based low complexity coherent heterodyne receiver therefore provides another promising alternative to direct detection receivers. With such clear sensitivity gains available from coherent detection, even without significant additional complexity, its implementation in future PONs is anticipated.

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References