Coherent ONU Designs for 50 Gb/s/λ PON

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Abstract: The required complexity of coherent technology has always been a show-stopper in optical access networks. Here, the recent compelling research activities in low-complexity coherent PONs are reviewed, and their feasibility for 50 Gb/s/λ is investigated.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.1660) Coherent communications.

1. Introduction

The conventional signal transmission, e.g., on-off keying (OOK), in optical access networks is reaching a saturation point due to continuously growing number of subscribers, connected devices per subscriber, and increasing bandwidth demands per device/application in residential areas and businesses [1]. With the upcoming mobile technologies such as 5G and beyond, there will also be a convergence between fixed and mobile access networks in the form of mobile front-haul networks using the same passive optical networks (PONs) infrastructure [2, 3]. Therefore, the IEEE 802.3ca Task Force is in the process of standardising 25G, 50G and 100G per wavelength (λ) in the form of 100G Ethernet PON [4,5]. In the quest for transceiver (TRx) technologies for PONs beyond 10G per λ, the key requirement is the coexistence with the previous generation of PONs, i.e., supporting the same power budget ($\geq$29 dB) and reach ($\geq$20 km) requirements, whilst reducing cost-per-bit. This brings the challenges of decreasing chromatic dispersion tolerance, the reduction in optical power budget due to the increasing bit rate, and the use of higher bandwidth components.

Beyond IM-DD OOK systems, several innovative TRx technologies, which can be grouped into two categories as DSP-aided direct detection (DD+DSP) and low-complexity (simplified) coherent TRxs (summarised in [6]), have been proposed to overcome such challenges. In both approaches, DSP serves for enhancing the TRx performance, yet with different functionalities. In DD+DSP TRxs, it is used to mitigate the non-ideal response of the low-cost optics and inter-symbol interference caused by the limited bandwidth whereas in a low-complexity coherent receiver, DSP is performed to mitigate the phase noise to realise advanced modulation schemes and for the compensation of channel impairments. The interest in using DSP in PONs started due to the trend in CMOS node size, i.e., reducing the chip size by half every two years, which leads to roughly a 30% reduction in power consumption, as discussed in [7]. On the other hand, photonic integration does not have the potential to scale comparably with the CMOS technology. Thus, it is reasonable to anticipate that DSP with moderate complexity, assumed to be a good indicator for cost, will be deployed for low-cost short- and medium-reach applications in the near future.

In this paper, we compare the sensitivity and dispersion tolerance of promising 50G per λ low-complexity coherent versus DD+DSP optical network unit (ONU) technologies including some experimental demonstrations. Herein, low-complexity coherent receivers with optical complexity (the number of required optical components) approaching that of DD+DSP TRxs are only considered. Furthermore, the required ADC bit resolution is analysed to evaluate the DSP complexity to explore the lower limits on the digital receiver hardware complexity.

2. Low-complexity Coherent ONU Designs

Despite the benefits of coherent technology [8], it comes at a greater financial cost due to the high optical complexity of coherent TRxs. The cost requirements for an ONU are more stringent than an optical line terminal (OLT), and thus, it is critical to realise polarisation-independent (PI) reception, which enables the implementation of a single polarisation coherent receiver using no polarisation tracking unit, to implement a low-complexity coherent ONU.

The proposed solutions for PI operation can be grouped in two categories, namely OLT- and ONU-based solutions. The ONU-based solutions typically do not require any extra components in the OLT. However, a polarisation beam splitter (PBS) is required to receive both polarisation states either before mixing with a local oscillator (LO) laser, such as *Ciaramella-Rx* proposed in [9], or after, such as *Glance/Altabas-HetRx* proposed in [10] and tailored to high-speed links in [11], as illustrated in Fig. 1. These receivers allow DSP-free operation, and hence, they are also referred to as "quasi-coherent" receivers or "coherent amplification". However, they have reduced dispersion tolerance since the phase information is lost due to envelope detection, and in their present forms, they are not suitable for detection of multi-level signals, i.e., 4-PAM, which causes a scalability issue, particularly for 50 Gb/s/λ and beyond.

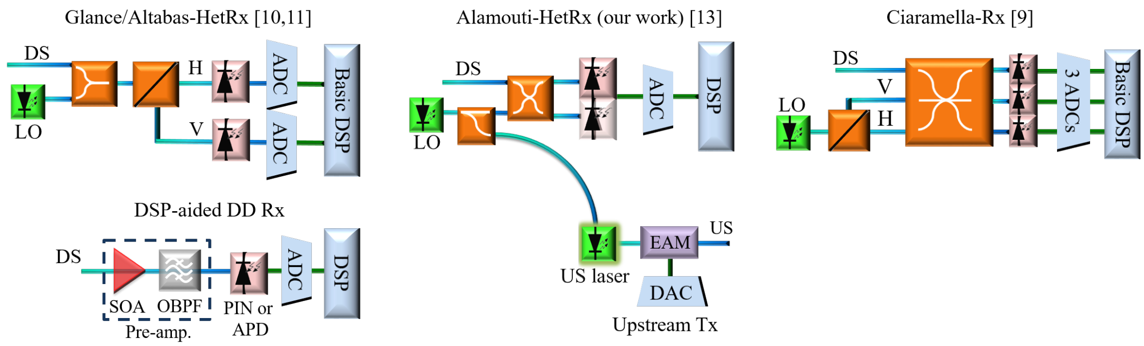

Fig. 1. The low-complexity coherent and DD Rx designs. Alamouti-HetRx can be realised using either a balanced or single-ended photodiode. DS/US: Downstream/upstream signal. EAM: Electro-absorption modulator. SOA: Semiconductor optical amplifier.

The OLT-based approaches shift the complexity from the ONU to the OLT side. Although this increases the required complexity of the OLT compared to an IM-DD OLT, one can build a coherent ONU TRx using optoelectronic hardware with a complexity comparable to that of the IM-DD ONU TRx counterpart when combined with heterodyne detection. Heterodyne reception also allows the simultaneous use of an ONU laser both as upstream source and downstream LO lasers, as shown in Fig. 1 and demonstrated in [12]. In these approaches, the symbols are precoded across both polarisation states such that the receiver can recover the transmitted symbols independently of the signal/LO state of polarization. This can be realised using an external polarization modulator, so-called polarisation scrambling [13], which operates at twice the symbol rate to precode the symbols for half of the symbol period. Therefore, it comes at the expense of a doubling in bandwidth requirement. Alternatively, polarization-time block (also known as Alamouti) coding precodes the symbols orthogonally in pairs over both polarisation states which allows to recover the symbols without increasing bandwidth requirements. Both techniques are compatible with a dense WDM system, however Alamouti coding exhibits an inherent 3 dB better sensitivity compared to polarization scrambling at the price of requiring DSP, as detailed in [14]. The fundamental sensitivity limits and the relative merits of these low-complexity coherent solutions operating at 10.7 Gb/s are further discussed in [15].

Initially, the sensitivity limits of low-complexity coherent receivers operating at 25 Gb/s/λ were assessed in simulations. In this analysis, an LO laser with a power of 10 dBm, a linewidth of 1 MHz, and a relatively intensity noise (RIN) of -140 dB/Hz, and the photodiodes with a responsivity of 0.5 A/W and a temperature of 300 K were assumed. *Alamouti-HetRx* with QPSK, *Ciaramella-Rx* with duobinary and *Glance/Altabas-HetRx* with OOK signalling exhibit the sensitivities of -39.6 dBm, -39.1 dBm, and -35.5 dBm at a BER of 4×10^{-3}, respectively, as shown in Fig. 2. If a single-ended PD is used for *Alamouti-HetRx*, offering the same optoelectronic hardware compared to the DD+DSP ONU, the sensitivity limit reduces to -36.2 dBm. Over 20 km of SSMF, the sensitivities of -37.4 dBm and -32 dBm were achieved experimentally using *Alamouti-HetRx* with a balanced and single-ended PIN PD, respectively [16] whereas the sensitivities of -37 dBm and -30.5 dBm were achieved using *Ciaramella-Rx* [17] and *Glance/Altabas-HetRx* [18]. *Alamouti-HetRx* requires a single ADC, is not limited by dispersion, and can realise high order modulation schemes, e.g., M-QAM, as demonstrated over 108 km of installed fibre [12]. However, it requires a greater DSP complexity compared to *Ciaramella-Rx* and *Glance/Altabas-HetRx* whereas the latter receivers require 3 and 2 ADCs, respectively, to realise >10 Gb/s/λ with no or minimal DSP. Since ADCs are the most power-hungry components in a receiver, *Alamouti-HetRx* may be the most favorable option due to its lower optoelectronics hardware complexity, lower number of ADCs and its scalability.

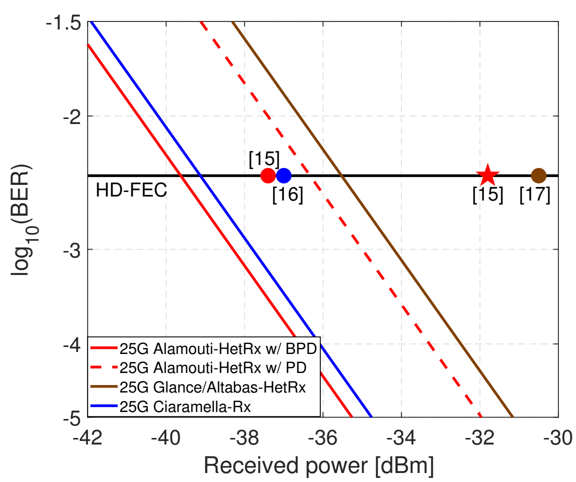

Fig. 2. Sensitivity limits for low-complexity coherent receivers at 25 Gb/s/λ. The lines and markers represent the simulation and reported experimental results, respectively.

3. 50 Gb/s/λ Coherent vs DD+DSP ONU Receiver Performance

Using the same simulation setup including a SOA (7 dB noise figure and 15 dB gain) followed by a 200 GHz ASE filter models [19] prior to a PIN PD, the sensitivity limits of *Alamouti-HetRx*s and a DD Rx versus the received power are shown in Fig. 3(a). They are also compared to the reported experimental demonstrations using 25 GBd 4-PAM DD+DSP

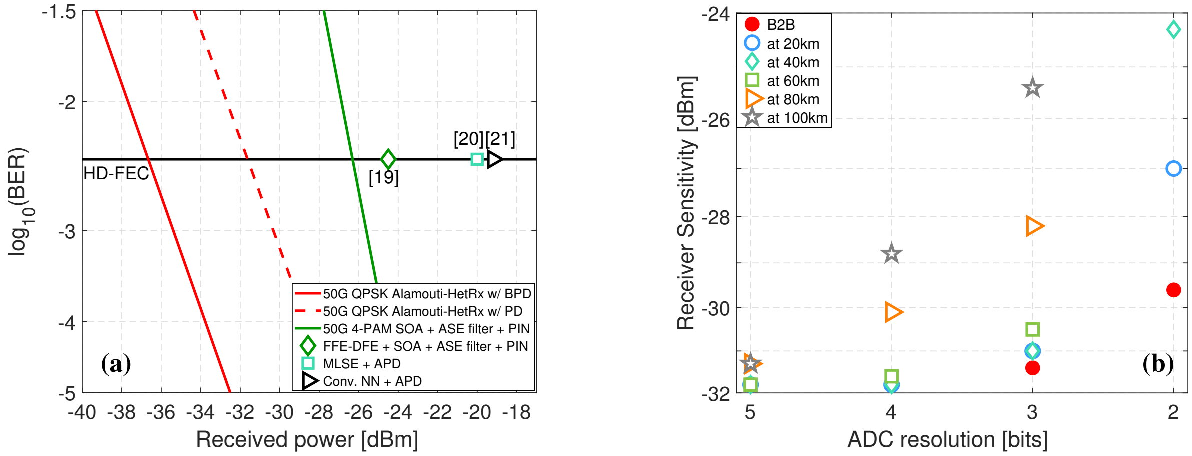

Fig. 3. Sensitivities for (a) *Alamouti-HetRx*s and DD Rx with a SOA+ASE filter in simulations and the reported experimental demonstrations using 50G DD+DSP TRxs. (b) The sensitivities using *Alamouti-HetRx* with a PD versus ADC bit resolution at different PON transmission distances.

TRxs with pre- and post-equalization. The simulation results suggest the sensitivities of -36.6 dBm and -31.7 dBm for *Alamouti-HetRx*s using BPD and a single-ended PD, respectively. The 5 dB penalty is due to the inherent 3 dB penalty (removing one branch of a 3-dB coupler) and the lower RIN value (-140 dB/Hz). Nevertheless, a DD Rx using a SOA offers 4.9 dB (-26.31 dBm) less than that of *Alamouti-HetRx* using a PIN PD. Furthermore, 4-PAM O-band transmission experiments achieving a sensitivity of -25 dBm using DSP-DD TRx with a SOA-PIN PD [20], -20 dBm using pre-/post-equalisation and an APD [21], and -19.2 dBm using machine learning and an APD [22] over 20 km of SSMF have been recently reported. These demonstrations present the feasibility of 50G ONU DD TRxs using various DSP techniques whilst avoiding an excessive increase in complexity compared to the 25G optical hardware.

A 2-bit ADC is required to detect a 4-PAM signal with no DSP. Thus, the use of a 3-bit ADC would be a reasonable choice for a DD+DSP ONU TRx. The sensitivities using *Alamouti-HetRx* with a PIN PD with respect to the ADC bit resolution were plotted in Fig. 3(b) to assess the feasibility of the required DSP at different distances. The penalty was found to be 1.5 dB up to 60 km for 3-bit, and increased to 2 dB at 80 km for 4-bit ADC resolution. These results indicate that sufficient performance can be achieved using *Alamouti-HetRx* with a low resolution (3-bit) ADC, which enable significant savings in the complexity and power consumption of the ONU electronics. Last but not least, the burst-mode (BM) operation in PONs is an important concern for coherent technology. It was recently demonstrated that *Ciaramella-Rx* offers a sensitivity of -29 dBm at a BER of $\times 10^{-2}$ for 50 Gb/s US transmission in a BM operation [23]. showing the feasibility of simple low-overhead AC-coupled BM operation using a coherent TRx [23].

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