# Simplified Coherent Optical Network Units for Very High Speed Passive Optical Networks

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**Future passive optical networks (PONs) for 200 Gb/s/$\lambda$, and beyond, pose a significant technological challenge. The use of coherent technology in access networks provides a great solution based on concepts from mature technologies to achieve the speeds needed for Very High-Speed PON (VHSP). In this paper, we provide an overview of the currently demonstrated technologies and propose a possible simplified optical network unit (ONU) for time-division multiplex PON (TDM-PON). The proposed ONU uses a single polarization heterodyne receiver, using either a balanced photodiode or a single-ended one and an electro-absorption modulated laser (EML)-based transmitter. The experimental demonstration using the proposed ONU in a bidirectional, symmetrical transmission over fiber distances of 20 km and 40 km shows the viability of the technology. The downstream direction achieves a power budget of 34.3/29.3 dB for 20 km and 33.9/29 dB for 40 km, for a balanced/single-ended receiver, whereas the upstream transmission achieves 29.3 dB for both scenarios.**

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## 1. INTRODUCTION

Recently, the International Telecommunications Union Telecommunication Standardization Sector (ITU-T) has started the study on the next Passive Optical Network (PON) standard, with the working title of Very High Speed PON (VHSP) [1], aiming for line rates beyond 50 Gb/s, driven largely by future technologies requiring large bandwidth. These technologies are generally thought to be 6G backhaul, as well as the forecast increase in business demand for bandwidth, which can be served by PON in a very cost-effective manner. Whilst decisions on what technologies are recommended for this standard are not expected for the next years, research should focus on providing viable solutions for the likely requirements.

Studying the past PON standards, estimations of the likely requirements can be made [2]. It is clear that the optical distribution network (ODN) needs to be reused, as it is a large part of the cost of the network, and reusing can save millions of dollars for the operator [3]. There are over a billion households and businesses served by fiber [4] and most of them are done so via PON. As such, future standards will have to operate with similar loss budgets to current standards, as well as be able to handle the fiber characteristics of the ODN in use.

Similarly, wavelength allocation needs to be carefully considered. The future PON will have to coexist with legacy standards, as operators may use the same fiber to serve different customers with different technologies. All current PON standards have upstream wavelength in the O-Band and Higher Speed PON (HS-PON) [5] has downstream placed in that band as well. These lead to coexistence issues with the next PON standard, as there is little unallocated wavelength left in the O-band. Previous standards at low speeds could move transmission on the downstream side to the L-band, however at linerates >50 Gb/s this is hard to achieve, as chromatic dispersion significantly degrades signal quality, for direct-detection based transmissions [2]. This leads to the conclusion that either coexistence with a legacy standard needs to be dropped, or PON needs to move to technologies that allow transmission in other wavelength bands at the required datarates.

Datarate is a key consideration for VHSP. The most widely deployed PON standards are operating at a single wavelength and do not use any wavelength division multiplexing (WDM). Considering the ITU-T standards, these are GPON, XG-PON, and HS-PON, at datarates of 2.5 Gb/s, 10 Gb/s and 50 Gb/s respectively. Looking at this progression, shown in figure 1, it is likely that VHSP will need to be able to provide linerate of 200 Gb/s, ideally on a single wavelength to be considered a

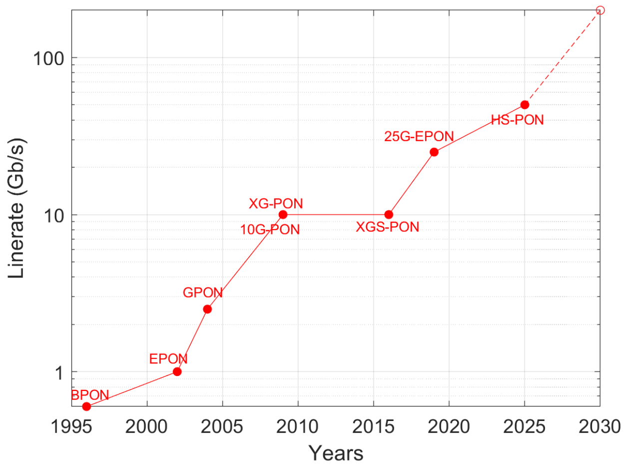


**Fig. 1.** Progression of PON standards over time

successor to the current standards.

This high datarate has started significant discussions in the research community regarding the transmission technology to be used. So far, all PON standards have realized transmission using intensity modulation with direct detection (IM-DD), as the associated costs with the transmitter and the receiver are low. However, it is already clear that high-speed transmissions struggle using IM-DD, with HS-PON introducing the possibility of digital signal processing (DSP) for the first time in PON [2]. This is necessary for a multitude of reasons and has clear benefits. The effects arising from chromatic dispersion for a 50 GBaud transmission even in the O-Band are resulting in significant penalties, as well as DSP allowing for use of 25G class components to be used in the 50 Gb/s transmission by compensating for the lower bandwidth of the already mature 25G class components. This technology can not be scaled for 200 Gb/s, as 200 GBaud would create a multitude of problems, both arising from fiber penalties as well as the very large bandwidth requirement imposed by the current standard's NRZ transmission [4].

For 200 Gb/s the spectral efficiency needs to be increased. This can be done by increasing the modulation order, going to PAM4 for example [6, 7]. These demonstrations show that with great difficulty, IM-DD can achieve 200 Gb/s and meet the PON requirements. However, these works are using technologies that are hard to use in PON, such as Raman amplification or circulators, as well as using very large filters in the DSP, leading to high power consumption. Other demonstrations of 200 Gb/s IM-DD solutions exist, using WDM, however, the technology requirement of these is similar to single wavelength standards at lower rates, and as such are not considered here.

Moving away from IM-DD for the first time is an attractive option in PON [8]. Following the wide adoption of coherent optical transmission in the core and metro networks, the technology is mature and proven. Moving to coherent transmission allows an easy increase in spectral efficiency by introducing the possibility for phase modulation and polarization division multiplexing (PDM). It also opens up the possibility of operation in the C-Band, as chromatic dispersion is easier to compensate in DSP than it is for IM-DD solutions. This leads to lower optical path loss and allows coexistence with existing technologies using the O-Band. Core networks are now moving to 800 Gb/s/$\lambda$ [9], showing the potential of the technology. However, full coherent transmission, using dual-polarization IQ-modulators, and reception, using the classical front end with two 90° hybrids and four balanced photodiodes is significantly more expensive than an IM-DD system using avalanche photodiodes (APD) for detection, and electro-absorption modulated lasers (EML) or directly modulated lasers (DML). Therefore, simplified coherent solutions are needed. These solutions have gained significant research interest [10].

In this paper, the prominent solutions for simplified coherent TDM-PON are presented for both the upstream and downstream directions. These technologies are introduced and discussed in detail in section 2. An optical network unit (ONU) is proposed based on the best possible technologies while keeping the cost low. This solution is presented in section 3. This proposed unit is experimentally validated over 20 km and 40 km of fiber. The details of the experimental setup are shown in section 4, whereas the results are presented and discussed in 5. The experimental demonstration shows power budgets exceeding E1 class for the balanced photodiode-based receiver and N1 class for the single-ended receiver for the downstream direction. The intensity-modulated upstream transmission achieves power budgets satisfying the N1 class requirements, as set by ITU-T for PON.

## 2. SIMPLIFIED COHERENT PON

Simplified coherent technology is a broad term used by the research community to describe technologies that loan parts of the full coherent link, offering simplifications to the transmitter, to the receiver, or to the DSP involved in the system to reduce the overall costs. These systems are also called coherent-lite [11], and have been deeply explored in recent literature, given increased interest from industry members, as the limitations of IM-DD force the inevitable change of technology. Herein, the solutions based on reducing the opto-electronic components are split into two main branches, dealing with simplified receivers for downstream transmission, and simplified transmitters for the upstream side of PON. This is due to the asymmetry in the PON layout, arising from the shared cost of the optical line terminal (OLT), where the network connects to the wider internet, and the need to keep the cost low at the ONU, as these are to be deployed to each individual user. From these the objective is clear: minimize the cost at the ONU, while more costly OLT solutions are permissible, as the cost is shared between all users on the network.

It is clear that even simplified coherent solutions will be more costly than IM-DD has been, purely from the increased number of components necessary for such transmission. Despite these drawbacks, all forms of coherent transmissions have advantages over IM-DD. By detecting the E-field directly, digital signal processing is significantly easier for chromatic dispersion, and adaptive equalization techniques used in long-haul transmission can easily be adopted to suit the needs of access networks. Recently emerging research interest in link monitoring for fault sensing [12, 13] and quality of transmission evaluation [14] can also be adopted for PON in this case, giving operators the chance to have better metrics about the networks in question.

### A. Simplified Coherent Receivers

Simplified coherent receivers are most often mentioned in the downstream transmission of the network. When using simplified receivers, the transmission is most often assumed to have the full capabilities of a regular coherent link in both polariza-

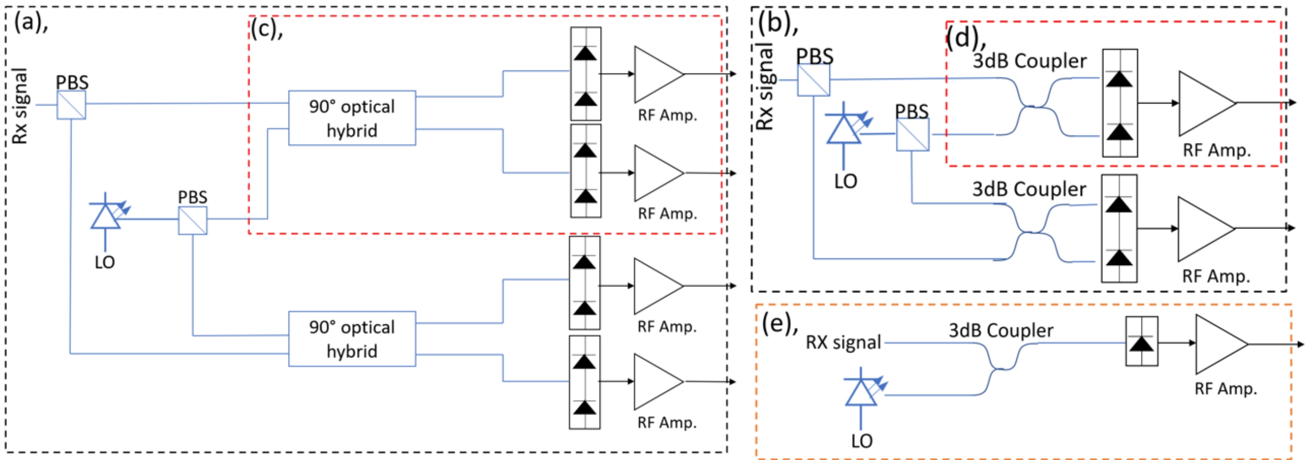


**Fig. 2.** Coherent receiver architectures. (a): Full coherent receiver (b): Polarization diverse heterodyne receiver (c): Single polarization intradyne receiver (d): Single polarization heterodyne receiver (e): Minimal coherent receiver

tion multiplexing and phase modulation. Simplified coherent receivers were first proposed at the birth of coherent transmission technology when limited DSP capabilities created obstacles in the equalization and phase tracking. As such, proposals using dedicated mechanical polarization tracking, or transmitting redundant information on both polarizations using polarization scrambling were investigated [15, 16]. However, these have not gained traction in the core networks, as by the time coherent was introduced, compute power had caught up to allow real-time DSP for polarization multiplexed signals.

Lately, simplified coherent has reemerged as a research interest, due to the cost-saving it enables at the receiver. This idea is particularly viable for PON, where the ONU cost is to be minimized. There are multiple techniques for reducing the component number at the ONU. Here, two will be discussed, heterodyne detection, and single polarization detection. However, to understand these receivers, one must start from a full coherent receiver as shown in figure 2a. The full coherent receiver with the four balanced photodiodes, the two polarization beam splitters and the two 90° optical hybrids offer room for reducing the number of components.

Moving to heterodyne detection from the conventional intradyne effectively doubles the bandwidth requirement, however, allows a reduction in component numbers, as well as the removal of some costly components in the receiver. This simplification allows the move from four balanced photodiodes to two, and translates to the same reduction in the number of transimpedance amplifiers (TIA), as well as allowing the use of 3 dB couplers in the place of the costly 90° optical hybrids. Additionally, since the 3 dB couplers have a marginally lower loss, better coupling to the photodiode allows an increase to sensitivity. This simplification is particularly attractive, as component bandwidth scales sublinearly with cost. Evidence for this can be found in the history of optical communication, where moving to higher bandwidth was always the preferred option over lighting up a new lightpath. This receiver is depicted in figure 2b.

The second simplification is using single-polarization receivers. Here the polarization beam splitter (PBS) is omitted, leading to two balanced photodiodes and a 90° optical hybrid in intradyne configuration, and a single balanced photodiode and a 3 dB coupler in heterodyne configuration. This receiver is shown in figure 2c and 2d. Such a a reduction of components is greatly reducing the cost of the unit. However, the issue of detecting the correct signal remains. Polarization scrambling at such high symbol rates is not feasible. There are other methods proposed by the research community, such as a differential group delay (DGD) based technique [17], however the most promising is the use of Alamouti coding [18]. This code is a space-time block code of rate 1/2, with orthogonal symbols. Originally proposed for radio frequency wireless communication, it can be easily used in optical communication in a simplified coherent setting, by modifying the adaptive equalizer at the receiver [19]. Alamouti coding is polarization independent, and any polarization state can be successfully received and decoded [19].

Lastly, a minimal coherent receiver should also be investigated. Replacing the balanced photodiode of the single polarization heterodyne receiver with a single-ended diode further lowers the cost, reducing the receiver to the local oscillator (LO) laser, a 3 dB coupler, and a photodiode, now having comparable complexity to IM-DD receivers. This receiver is shown in figure 2e. On the topic of simplified coherent receivers, it is also worth mentioning the research efforts in the area of 3x3 coupler-based receivers [20], these devices however have an increased number of I/O ports compared to the receivers detailed above. To provide a concise overview of the hardware cost of these receivers, a comparison table is presented in table 1. The comparison is valid assuming 16 QAM modulation and 200 Gb/s linerate.

The performance of these devices is key to evaluating their use in the future. Relative sensitivity compared to the full coherent receiver is a good measure of the performance trade-offs necessary for the simplifications. Dual polarization heterodyne receivers have the same theoretical sensitivity as the full coherent receiver [21], and in practical implementations, the sensitivity difference only depends on the insertion loss of components used. Moving to single polarization, using Alamouti coding, has however an inherent 3 dB penalty due to only detecting a single polarization of the signal. The minimal coherent receiver experiences an excess penalty due to only using a single port of the 3 dB coupler. This theoretical 3 dB penalty increases in practical implementations, as the lack of common mode noise cancellation leads to an increased effect of LO relative intensity noise (RIN).

Experimental demonstrations largely back the theoretical

**Table 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. (Assuming Nyquist bandwidth) (Balanced Photodiode (BPD), Photodiode (PD), Transimpedance Amplifier (TIA), Analog-to-Digital converter (ADC))

| | **Optical Components** | **Electrical Components** |
|---|---|---|
| **Dual Polarization Intradyne** | 2 PBS, 2 90° hybrids, 4 BPDs (12.5 GHz) | 4 TIAs (12.5 GHz), 4 ADCs (12.5 GHz) |
| **Dual Polarization Heterodyne** | 2 PBS, 2 3-dB couplers 2 BPDs (25 GHz) | 2 TIAs (25 GHz), 2 ADCs (25 GHz) |
| **Single Polarization Intradyne** | 1 90° hybrid, 2 BPDs (25 GHz) | 2 TIAs (25 GHz), 2 ADCs (25 GHz) |
| **Single Polarization Heterodyne with Balanced Photodiode** | 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) |

results. There was no sensitivity difference found between intradyne and heterodyne receivers [22]. As for the minimal coherent receiver, the penalty has been reported at 5.5 dB [23]. All proposed technologies have already been demonstrated to exceed the minimum power budget class defined for PON by ITU-T (N1 class, >29 dB), and some have achieved significantly higher power budgets. It has been shown that linear predistortion to reduce transmitter gain-imbalance can improve the power budget by 0.9 dB [23], and an additional 1 dB can be gained using a simple phase-shift based non-linear precompensation [24]. These experimental demonstrations are summarized in table 2.

At this point it is important to mention the DSP requirements of such a receiver. The power consumption of the single polarization heterodyne receiver can be divided into three main parts, the current draw of the photodetectors, the analog-to-digital converters (ADC), and the ASIC's power draw, mainly arising from the DSP inside. In this regard, simplified coherent still has a benefit over the IM-DD demonstrations, where extensive and computationally expensive DSP is used [7]. As for the difference to full coherent, the advantage is still present, as the reduced number of input channels necessarily reduces the number of operations required, such as for chromatic dispersion, only one polarization needs to be compensated. In an additional benefit of single-channel detection, receiver IQ skew compensation is not necessary. The adaptive equalizer is of a similar complexity to full coherent solutions. The viability of real-time signal processing of these type of signals has been shown recently [25].

### B. Upstream Transmission in Coherent PON

In the upstream direction, the complexity allocation is reversed: the OLT receiver could tolerate more complexity, while the ONU transmitter complexity should be kept minimal. To achieve this target, an architecture combining an IM-based transmitter with a coherent receiver is a convenient approach.

There are two IM schemes: direct modulation and external modulation. Regarding the former, the DML approach, using vertical-cavity surface-emitting laser (VCSEL) or distributed feedback lasers (DFB), represents the most cost-effective solution. Concerning external modulation, the most used technologies are the electro-absoption modulator (EAM) and the Mach-Zehnder Modulator (MZM)-based transmitter. Most often EAMs are integrated with a DFB laser forming an EML. EML is more cost-effective than MZM, but has a larger chirp and generates larger non-linear distortions. DML systems generate even larger chirp values and non-linearities. Proper chirp management could enhance system performance when properly combined with chromatic dispersion in IM-DD systems [27]. However, using coherent detection with full chromatic dispersion digital compensation, the chirp is a source of signal degradation [28, 29], especially when operating in burst-mode. Moreover, the DML adiabatic chirp generates an additional non-linear distortion. Additionally, the DML operated in burst-mode suffers from self-heating wavelength drift [30, 31], which complicates the frequency tracking and can result in sensitivity penalties due to generating a frequency offset between the transmitter laser and the LO of the coherent receiver [32]. Then, so far, EML and MZM options have been preferred for high-speed PON applications with coherent detection [25, 26, 33–36]. Device non-linearity is another factor to take into account when selecting an optical transmitter. An MZM can operate in a linear regime for higher extinction ratios than EML and DML. Then, non-linear mitigation schemes [35] should be introduced in order to exploit the cost-effectiveness of EMLs and still achieve similar performance than using a MZM.

Current DMLs can deliver output powers of around 11 dBm [37]. Due to the insertion losses of the external modulators, EML- and MZM-based transmitters deliver lower output powers than the DMLs. To reach similar transmitted powers, a booster optical amplifier is commonly combined with the EML or MZM, in order to reach the demanding PON power budgets. To implement this, the Semiconductor Optical Amplifier (SOA) is the preferred technology due to its reduced size and integration capabilities [38–40].

Another key factor to consider is the choice of the modulation format. The simplest IM format is the binary non-return-to-zero on-off keying (NRZ-OOK), which, moreover, has an intrinsic higher sensitivity and is more resilient to device nonlinearities. Then, it has been the choice for all PON generations standardized up to now (based on IM-DD). However, currently available devices impose strong bandwidth limitations when sticking

**Table 2.** Experimental demonstrations using simplified coherent receivers for 200 Gb/s/$\lambda$ for PON applications

| Simplified receiver type | Modulation format and symbol rate | Reported Power Budget |
|---|---|---|
| **Dual Polarization Heterodyne** | 50 GBaud PDM-PAM4 | 32.5 dB [26] |
| **Single Polarization Intradyne** | 50 GBaud 16 QAM | 33 dB [22] |
| **Single Polarization Heterodyne with Balanced Photodiode** | 50 GBaud 16 QAM | 35 dB [24] |
| **Minimal Coherent** | 50 GBaud 16 QAM | 29 dB [23] |

with NRZ-OOK in very high-speed applications. As an alternative, higher-order formats, such as duobinary, PAM-M and multi-carrier formats have been proposed to increase the spectral efficiency [2, 41–43]. In particular, PAM-4 has been widely analyzed and used in the data-center ecosystem, which makes this format a popular alternative for next-generation PON systems.

We compare two recent research proposals that have shown feasible 200 Gbps/$\lambda$ PON operation using IM and coherent detection [26, 34]. Both proposals use the PDM scheme to transmit 100 Gbps/$\lambda$ per polarization, using 50 GBaud PAM-4 format, over 20 km of SMF in C-band. They both use full coherent detection at the receiver. The main difference between them is the employed optical transmitter and the related DSP. In [26], an MZM is used amplified by an EDFA, whereas in [34] an EML plus SOA is employed. The MZM solution uses only linear equalization. To mitigate the stronger distortions introduced by the EML, the authors proposed the use of maximum likelihood sequence estimation (MLSE) and a pre-distortion scheme using a look-up table. The authors verified the superiority of MLSE over a Volterra Non-Linear Equalizer to improve the sensitivity. A power budget of 29.4 dB is achieved using the EML-based system, having a sensitivity of -19.4 dBm and a transmitted power of 10 dBm. In the MZM-based approach, a power budget of 32.5 dB is attained with a launch power of 13 dBm and sensitivity of -20.2 dBm. In both cases, a pre-FEC BER of $10^{-2}$ is targeted.

Based on the previous comparison, we observe that the sensitivity of the MZM-based system is only 0.8 dB better than the EML approach. To achieve this result, a non-linear equalizer has to be included in the EML-based solution. However, this extra complexity is placed at the OLT side, which is a centralized and shared element. In contrast, the ONU cost is reduced by using an EML instead of a MZM, and a SOA rather than an EDFA. Moreover, the insertion losses of an EML are smaller than an MZM, thus saving continuous wave laser power. In summary, we consider that the use of EML + SOA should then be preferred in cost-sensitive PON applications.

## 3. PROPOSED OPTICAL NETWORK UNIT

Based on the technologies presented, we present a solution for 200 Gb/s/$\lambda$ symmetrical, bidirectional PON, using simplified coherent technology. At the OLT, the solution is to use a full coherent transmitter and receiver, and the simplified coherent approach is exploited at the ONU. As such the design of the ONU is explored in more detail. There are three key aspects of the ONU. The receiver, the transmitter and some form of optical component to separate/join the downstream and upstream traffic, allowing the efficient bidirectional use of the fiber already deployed in the ODN.

For the simplified coherent receiver, the two most cost-effective approaches are the two single polarization heterodyne receivers, either using a balanced photodiode or a single-ended one. Both these receivers will be investigated in an experimental setting for viability in the proposed system.

The upstream transmission is realized using 50 GBaud PDM-PAM4 signals. These signals can be created using cost-effective DFB lasers combined with EAM, leading to an EML package. Demonstrations of co-packaged PDM EMLs already exist [44], and the full coherent receiver at the OLT can efficiently decode the signals. The PDM scheme shown in figure 3 needs careful engineering to generate two EMLs with low-frequency offset. Alternatively, DP-EML can be constructed with one DFB, two EAMs and a couple of polarization rotators as explained in [44]. For higher launch power a SOA should be integrated into the system[45]. Although SOA have in general significant polarization dependent gain, there are options with minimal gain imbalance [46], which would be preferred for PON aplications.

The bidirectional use of the fiber is a key component of PON. Finding an approach that has low insertion loss, as well as able to isolate the incoming traffic from the transmitted one to avoid damage to the optical components is key. Recently there have been some demonstrations using circulators [47], however, these devices are often costly and hard to integrate into the ONU. We propose the use of a red-blue optical diplexer [48], which separates the signal from the common port based on wavelength. These devices are bidirectional, and have a low insertion loss, typically ∼0.5 dB. For optimal operation, there is a wavelength gap (∼ 10 nm) between the upstream and downstream signal. This also reduces the non-linear effect of these signals on each other, allowing higher launch powers over the fiber network.

Summarizing the above, the proposed ONU can be seen in figure 3. The simplified coherent receiver should either be the single polarization heterodyne receiver with a balanced photodiode shown in figure 2d or the minimal receiver shown in figure 2e.

## 4. EXPERIMENTAL DEMONSTRATION

The experimental demonstration considers a realistic model of a PON. The experimental setup is shown in figure 4. Two fiber distances are considered, 20 km for the standard PON reach, and 40 km for the extended reach networks. Both of these fibers are standard single-mode fibers (SSMF), with 4.04 dB and 7.8 dB loss respectively. These adhere to the specifications of ITU-T for the current PON, and since the reuse of the ODN is expected, the fiber infrastructure should not change in the future. The ONU side of the model uses the proposed architecture shown in figure 3, whereas the OLT uses a full coherent front-end for both the transmission and the reception of the signal.

The system performance is evaluated in terms of sensitiv-

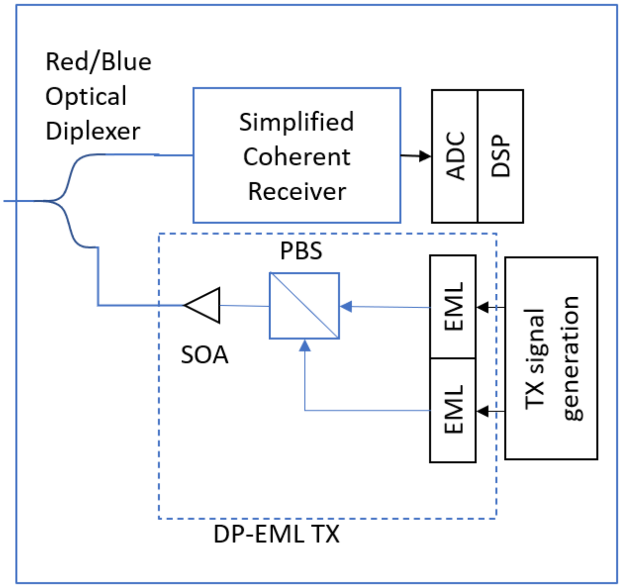


**Fig. 3.** The proposed ONU for 200 Gb/s/$\lambda$ PON system. Semiconductor optical amplifier (SOA), Electro-absorption modulated laser (EML), Analog-to-Digital converter (ADC), Polarization beam splitter (PBS), Digital signal processing (DSP), Dual polarization electro absorption modulated laser (DP-EML)

ity to received optical power. Power budget is derived from these sensitivity measurements. Sensitivity is defined to be the received optical power level where the pre-FEC bit error rate (BER) is $10^{-2}$. This is in line with the current HD-FEC threshold used in HS-PON[5].

The downstream signal is created digitally, with precompensation applied to reduce IQ skew and flatten the gain spectrum [23]. This is uploaded to an arbitrary waveform generator (AWG) operating at 100 GSa/s. The signal is Alamouti-coded dual-polarization, 16 QAM modulated, and pulse-shaped with a root-raised cosine (RRC) filter with 0.01 roll-off. For the optical modulation, a commercial dual-polarization IQ-modulator was used with a 3 dB bandwidth of 40 GHz. The carrier frequency of the signal is 1539 nm. The signal is then amplified by an EDFA to achieve the required launch power. The signal is coupled into the fiber using the red/blue diplexer, which has an insertion loss of 0.9 dB. Launch power is measured at the input to the fiber. At the receiver, the signal is first decoupled from the upstream signal using another red/blue diplexer. The signal then is passed through a variable optical attenuator (VOA) for setting the power into the receiver. The receiver is either of the aforementioned single polarization heterodyne receivers. These receivers are constructed of discrete components. An ECL laser is used as a local oscillator with linewidth of 100 kHz and power of 16 dBm. The photodiodes both have bandwidth of 70 GHz, and an RF amplifier with 16 dB gain and 60 GHz bandwidth is used before capturing the signal using a digital sampling oscilloscope (DSO) at 256 GSa/s and 70 GHz analog bandwidth.

Signal processing at the receiver is performed offline. First, the intermediate frequency is estimated and the signal is converted to baseband, followed by timing and clock recovery, as well as resampling to 2 Sa/symbol. Following this, chromatic dispersion is compensated. Adaptive equalization is performed using a decision-directed least-means-squared (DD-LMS) algorithm [19]. Finally, BER is calculated for the sample.

The upstream signal is first generated offline, and is pulse shaped with a RRC filter with 0.4 roll-off factor. For the pre-processing of the 50 GBaud PAM-4 signal, look-up table (LUT) based pattern dependent predistortion [49] is applied to mitigate the nonlinear impairments of the transmitter circuit. This signal is then uploaded to an AWG operating at 100 GSa/s. The optical modulation is done through an integrated EML package consisting of a DFB-laser and an electro-absorption modulator. Due to equipment limitations, the polarization multiplexing is realized using the split-delay-recombine [26] method, creating a delay of ∼300 symbol delay between the two polarizations. This is more than any time domain filter in the system, and as such the signals can be considered uncorrelated. After recombination, the signal is amplified using an SOA, with a nominal gain of 17 dB. The carrier frequency of the transmission is 1552 nm. The red/blue diplexer is used to couple into the fiber. Similarly to the downstream transmission, the launch power is measured at the input to the fiber. At the receiver, after separating the downstream and upstream channels the signal is detected using a class 40 integrated coherent receiver (ICR). The LO laser in this case is and ECL with 100 kHz linewidth and 16 dBm power. Digitization and capture of the signal is performed using a 4-channel DSO at 256 GSa/s and 70 GHz analog bandwidth.

The DSP consists of the following components. First IQ skew inherent to the ICR and electrical front-end is compensated. This is followed by chromatic dispersion compensation, and resampling to 2 Sa/s. The adaptive equalizer uses the DD-LMS algorithm. To improve performance MLSE is performed as a nonlinear equalizer. The memory depth of the equalizer is 2 symbols. Finally, the signal is decoded and BER is calculated. This DSP stack has a very fast convergence time (∼144ns), which is suitable for burst mode detection [34].

## 5. RESULTS AND DISCUSSION

The presentation and discussion of the results are broken into two main sections, first presenting the results for 20 km fiber transmission, which is more typical for PON ODNs, and later discussing the extended reach networks of 40 km fiber length.

Over the 20 km fiber the optimum launch power was measured at 11 dBm. This power is obtained by plotting the power budget curve for the receiver after fiber transmission and finding the maximum, and the corresponding launch power. For the balanced photodiode receiver, the sensitivity at this power, after 20 km fiber was -23.3 dBm, leading to a maximum power budget of 34.3 dB. This is in excess of ITU-T specification, and achieves E1 class operation. These results are shown in figures 5, 6. The minimal coherent receiver was also investigated. As expected the optimum launch power remains the same at 11 dBm, however, the sensitivity is reduced to -18.3 dBm at this power level, after 20 km fiber. This leads to a maximum power budget of 29.3 dB, which exceeds the 29 dB requirement of the N1 class operation as specified by the ITU-T PON standards. These results are also shown in figures 5, 6. The sensitivity, and hence the power budget gap between the balanced photodiode driven receiver to the single-ended one is observed at 5 dB. This is more than the theoretical minimum of 3 dB and suggests that LO RIN is creating a large penalty in this experimental setup.

Upstream transmission is evaluated similarly. Here, the optimum launch power is reduced, and was found to be 10 dBm.

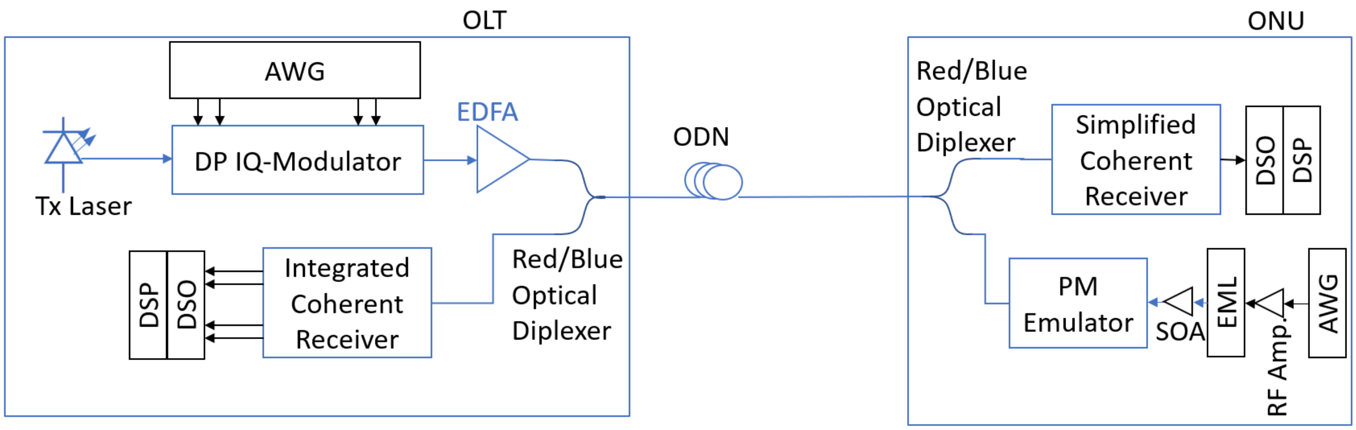


**Fig. 4.** The experimental setup for 200 Gb/s/$\lambda$ transmission. Dual polarization In-phase/Quadrature(DP-IQ), Optical line terminal (OLT), Erbium-doped fiber amplifier (EDFA),Polarization multiplexing (PM), Semiconductor optical amplifier (SOA), Electro-absorption modulated laser (EML), Arbitrary waveform generator (AWG), Digital Sampling Oscilloscope (DSO), Digital signal processing (DSP)

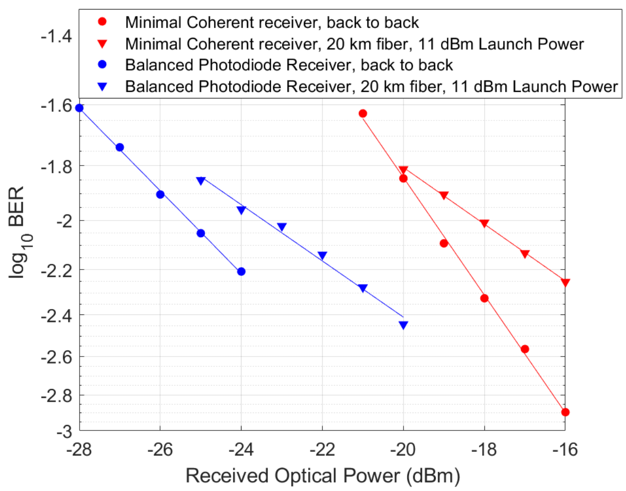


**Fig. 5.** Sensitivity for 20 km fiber bidirectional downstream transmission

This is due to the limitations of the SOA used in the experiments, where gain saturation adds additional non-linearity, and as a consequence a sensitivity penalty to the system. This could be overcome by using an SOA with a higher saturation power, as the gain requirement is relatively small compared to an MZM-based system. This is due to the larger output power of the EML module at 1 dBm, compared to the typical output power of the MZM at $\sim$-10 dBm. The sensitivity at this power was -19.3 dBm, after 20 km fiber, leading to a maximum power budget of 29.3 dB. This is also in excess of ITU-T N1 class specification. The sensitivity curve for optimum launch power can be seen in figure 7, and the power budget is shown in figure 8.

The results for the 40 km fiber are similar in large. The upstream receiver performs exactly the same, as the launch power is still limited by the SOA gain saturation, and other fiber-related effects are efficiently mitigated by the DSP applied, as shown in figure 7. As such the power budget is the same at 29.3 dB with 10 dBm launch power. This is shown in figure 8. The downstream direction has different results though, here the increased fiber length decreases the optimum launch power to 10.5 dBm, hence power budget degradation is observed. The new sensitivity at this power is -23.4 dBm for the balanced photodiode based receiver, and -18.5 dBm for the minimal coherent receiver,, after 40 km fiber. These lead to sensitivity numbers of 33.9 dB and 29 dB respectively, which are in excess of E1 class and N1 class power budgets. These results are shown in figures 9, 10.

Additionally, penalties arising from the bidirectional use of fiber were investigated. Sensitivity was measured in two scenarios for both directions of transmission. First, both directions are operating at optimum launch power, and second when one of the directions is turned off. There was no penalty observed, which is expected as there is a relatively large separation of the two wavelengths [48].

These results, summarized in table 3, show the viability of the technologies proposed and with the two different simplified receivers, these provide a choice for operators. The minimal coherent receiver is reduced in cost, due to the lower complexity, however, the co-packaging of photodiodes to form a balanced

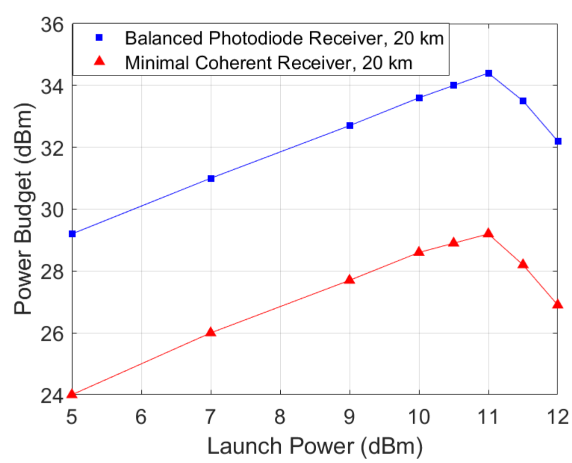


**Fig. 6.** Power budget for 20 km fiber bidirectional downstream transmission

**Table 3.** Summary of the experimental results. (Bidirectional transmission, 200 Gb/s/$\lambda$ symmetrical transmission)

| | Power budget with 20 km fiber | Power Budget with 40 km fiber |
|---|---|---|
| Downstream transmission with Single Polarization Heterodyne Receiver using Balanced Photodiode | 34.3 dB | 33.9 dB |
| Downstream transmission with Minimal Coherent Receiver | 29.3 dB | 29 dB |
| Upstream Transmission | 29.3 dB | 29.3 dB |

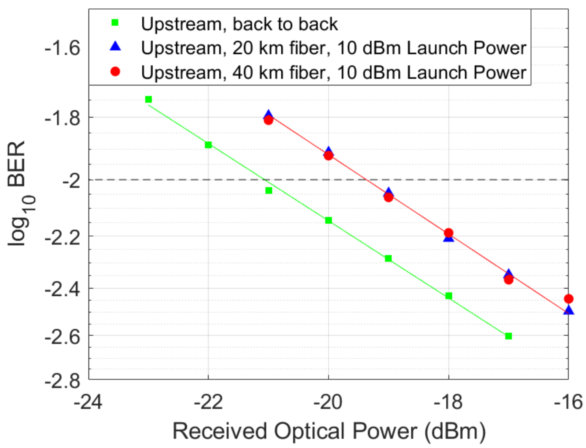


**Fig. 7.** Sensitivity for 20 km fiber bidirectional upstream transmission

pair might not be too much of an additional cost. It is also possible to reduce the LO laser power and still achieve high power budgets for the balanced photodiode case [23]. This would open up the possibility of a reduced laser cost, and may even make this solution more financially viable. As for the upstream, a fully integrated transmitter will likely achieve better results compared to the discrete component-based one, however, the current one already meets the minimum power budget requirement of PON.

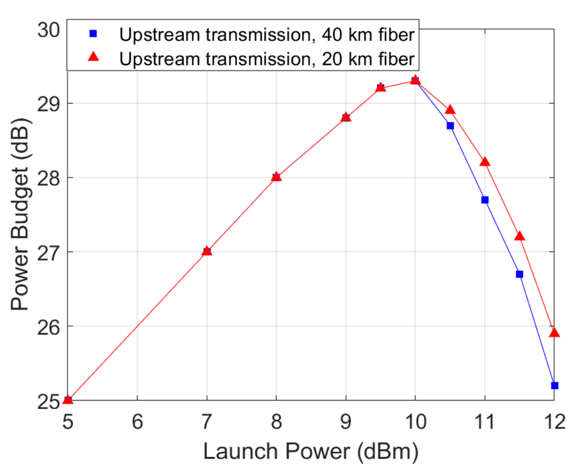


**Fig. 8.** Power budget for upstream transmission

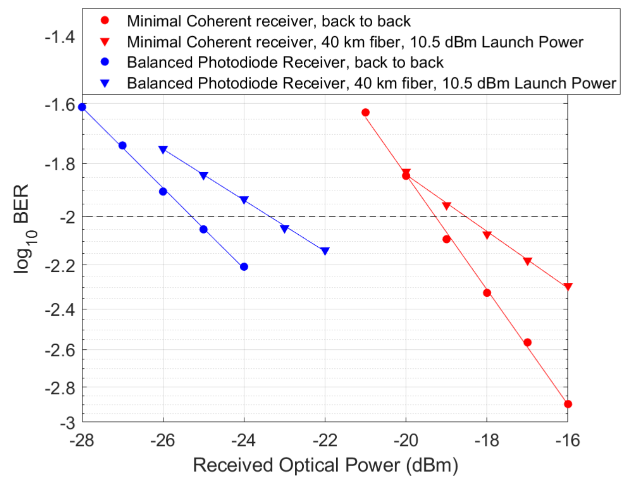


**Fig. 9.** Sensitivity for 40 km fiber bidirectional downstream transmission

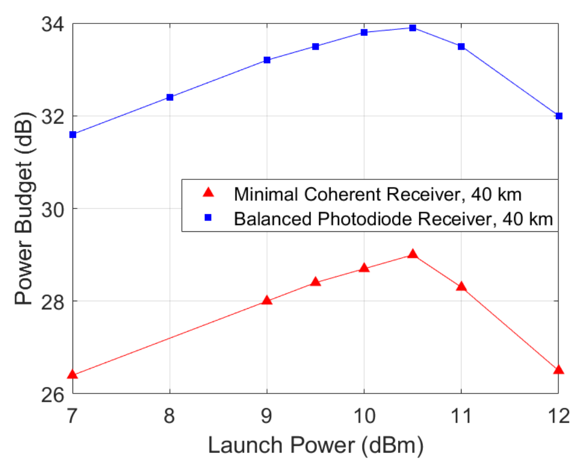


**Fig. 10.** Power budget for 40 km fiber bidirectional downstream transmission

## 6. CONCLUSIONS

This paper has provided an overview of coherent transmission-based technologies offering reduced overall system cost for PON applications. These technologies can be key in solving the challenges posed by the increase of datarate to the next PON generation. We have provided a proposal for a simplified coherent ONU, to minimize the cost whilst achieving 200 Gb/s/$\lambda$ transmission. To further show the viability of these technologies, a demonstration of 200 Gb/s/$\lambda$ bidirectional transmission was performed over fiber distances of 20 km and 40 km. There was no penalty observed due to the bidirectional use of fiber. The proposed solution achieves N1 class power budget (>29dB) for upstream and downstream (with either single-ended or balanced photodiode) with both reach 20 km and 40 km reach.

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## OPEN ACCESS AND DATA AVAILABILITY STATEMENT

 Data underlying the results presented in this paper are available at 10.17863/CAM.104366.

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