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Analysis of Conventional Direct Detection and Coherent Optical Receivers in Optical Access Networks †

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Abstract: This study evaluated the use of GFDM transmission in passive optical networks (PONs) by comparing the performance of coherent and non-coherent optical receivers using OptSim 2023.12sp2 and Matlab 2018b ®. The study concentrated on transmitting 10 Gb/s radio frequency signals over optical fiber, emphasizing the significance of high-speed fronthaul links for 5G networks. The findings demonstrated that coherent detection markedly enhances receiver sensitivity by approximately 3 dB compared to direct detection, thereby augmenting the capacity of optical fronthaul networks despite the elevated cost. Additionally, the study recommended investigating pre- and post-compensation techniques to mitigate signal dispersion in optical fibers for further performance optimization.

Keywords: IM-DD; coherent optical receivers; PON; optical access network

1. Introduction

The growing demand for higher data transmission speeds presents considerable challenges for network operators and service providers. Next-generation networks provide a crucial solution to address these challenges, particularly in complex scenarios involving advanced mobility, large user bases, and rigorous data requirements. Optical access networks are particularly well-suited for emerging applications such as mixed reality, augmented reality, holographic communication, the Internet of Things (*IoT*), and digital sensing. These applications necessitate high-capacity, low-latency, and high-reliability networks to ensure the delivery of quality experiences and adherence to the requisite Quality of Service (*QoS*) levels [1,2].

PONs have undergone significant advancements to meet the escalating bandwidth requirements and user numbers. Conventional direct detection (*IM-DD)* methodologies are being augmented by sophisticated techniques to augment network capacity. One such advancement is the G.989.1-Next-Generation Passive Optical Network 2 (*NG-PON2*) standard, which supports data transfer rates of up to 100 Gbps or more [3,4]. To attain these speeds, coherent detection—a technology heretofore employed in long-haul networks for its superior performance—is now being adapted for PONs. Coherent detection offers markedly enhanced receiver sensitivity in comparison to IM-DD, rendering it an optimal choice for fulfilling the performance expectations of contemporary optical networks [5,6]. The latest advances in digital signal processing (*DSP*) have further enabled coherent detection-based PON systems to support high-speed optical access networks with data rates exceeding 100 Gbps [7].

This study examines the potential applications of PON technology in the fronthaul link of a 5G mobile network, with a particular focus on comparing two optical transmission

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schemes: the two optical transmission schemes under consideration are intensity modulation with direct detection (*IM-DD*) and Coherent Transmission-Detection. Through co-simulation with OptSim 2023.12sp2 and Matlab2018b®, the performance of these schemes was evaluated using GFDM signals modulated with 4QAM and 16QAM over 20 km of single-mode fiber at a rate of 10 Gb/s [8].

The study's objective is to enhance the fronthaul link's capacity by considering the type of optical detection, modulation formats, and digital post-processing. The findings demonstrate that coherent transmission markedly enhances receiver sensitivity by approximately 3 dB compared to direct detection, indicating a considerable expansion in network capacity. However, the high cost of implementing coherent detection remains a significant drawback. Furthermore, the study investigates pre- and post-compensation techniques for dispersion in optical fibers.

Using BER and EVM analysis, this paper will compare receiver sensitivity between coherent and direct detection. Section 2 reviews previous work, Section 3 provides a theoretical analysis of detection methods, Section 4 discusses system architecture and co-simulation scenarios, and Section 5 presents the co-simulation results and summarizes the findings.

2. Related Works

The enhancement of optical system capacities represents a pivotal challenge driven by the expanding demand for data and the necessity for integration with existing technologies. The evolution of PONs aims to enhance their performance, with the deployment of coherent detection techniques offering notable advantages over direct detection. This approach has the potential to boost capacity and sensitivity. OOK (on–off keying) modulation is a prevalent choice in coherent detection systems due to its simplicity and efficacy. It facilitates implementation and compatibility with direct detection techniques, reducing system complexity. Moreover, its capacity to adapt to noise and turbulence conditions renders it a promising candidate for enhancing BER in PON-WDM networks. A modified OOK system was demonstrated to enhance BER performance and electrical signal-to-noise ratios (*SNRs*) in ID/MM systems. At a BER of 10^{-4}, a 2.2 dB and 4.2 dB improvement in SNR was observed between an optimized and an adaptive detection system, respectively. Moreover, a reduction in the power penalty of between 2.0 and 4.0 dB was observed at a BER of 10–12 under conditions of weak turbulence [9]. Another study [10] presented a 64 QAM phase-modulated system capable of transmitting at 168 Gbps over 170 km. This system demonstrated improvements in receiver sensitivity and a reduction in BER through coherent detection.

Building upon this line of inquiry, the work of [11] continues to serve as a foundational reference, illustrating a receiver sensitivity of −53 dBm at 311 Mb/s with an optical link budget of 50 dB through real-time data processing. The optical power/loss budget represents a pivotal aspect, necessitating the incorporation of intensity modulation/direct detection (*IM-DD*) solutions to attain a 29 dB budget, thereby ensuring compatibility with existing fiber-optic infrastructures [12]. Furthermore, the intricate nature of PON systems operating at 100G or above necessitates the incorporation of sophisticated components, including photon detectors and transimpedance amplifiers, which could potentially lead to increased costs and complexity. The study [13] presented a 100 Gb/s UD-WDM coherent PON system for fronthaul in 5G networks, improving receiver sensitivity to −26 dBm. These advances reflect continued progress towards faster and more efficient optical networks designed to meet the growing demand for data.

Consequently, recent research has demonstrated that, following a propagation distance of 120 km, a received coherent OFDM signal's radio frequency (*RF*) spectrum undergoes expansion due to chromatic dispersion and polarization mode dispersion (*PMD*) in single-mode fiber. OFDM technology is employed to mitigate these effects, offering a more cost-effective alternative to traditional OOK systems. Furthermore, it has been observed that by increasing the laser power from −16 dBm to 0 dBm, the Q factor improves significantly, and

the BER is reduced, indicating an improved system performance [14]. However, the authors do not mention the receiver sensitivity or if they are close to the values recommended by GPON standards.

3. Background

3.1. Direct Detection

Due to its simplicity and cost-effectiveness, direct detection is the prevailing technique in contemporary PONs. In this configuration, the optical signal is converted directly into an electrical signal by a photodetector, typically an inversely polarized photodiode. This generates a photocurrent that is proportional to the received optical power. The resulting electrical signal is proportional to the intensity of the modulated optical signal. However, this technique has significant limitations, as it only captures the optical signal intensity, omitting phase information, which limits the data transmission capability and reduces the spectral efficiency. Furthermore, the electrical signal is susceptible to various forms of noise, including thermal, shot, and photodetection noise, which can impair signal quality. Moreover, the encoding of the signal in a single polarization results in a reduction in both the spectral and power efficiency of the system [5,15].

The signal strength constrains the functionality of these devices, as they are only capable of detecting and demodulating the information present within the optical signal strength. Encoding the signal in a single polarization reduces both the spectral efficiency and the power efficiency of the system, and information regarding the signal phase is lost. The optical signal $E(t)$, as described by Equation (1), is converted into an electrical signal $i(t)$ at the output. This transformation results in the conversion of an optical power pulse into an electrical current pulse, as illustrated in Figure 1. This conversion enables the information to be processed and recovered. However, only the intensity information is retained, resulting in the loss of the phase of the original signal.

$$E(t) = A(t)e^{j\theta(t)}e^{j\omega(t)} \tag{1}$$

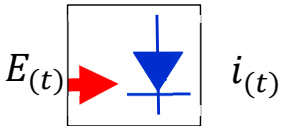


Figure 1. Scheme of direct detection on the photodetector.

The received optical signal is represented by three parameters: the amplitude, given by A; the phase, which is expressed as $e^{j\theta(t)}$, and the angular frequency, which is represented by $e^{j\omega(t)}$. The direct detection response is the electrical signal at the output of the photodetector $i(t)$,which is determined by Equation (2). This Equation shows that the electrical current is proportional to the optical field power $P(t)$ entering the receiver. The proportionality constant is related to the responsivity of the photodetector (R) and the thermal noise components generated in the photodetector process (θn). Consequently, the phase information of the transmitted signal is irretrievably lost [16,17].

$$i(t) = RP(t) + \theta n(t) \tag{2}$$

3.2. Coherent Detector

The coherent detection system utilized in optical networks is more intricate and costly than direct detection. It comprises a set of high-sensitivity photodiodes, a local oscillator, and various high-performance optical and electronic components. The coherent receiver's advanced design enables the complete extraction of information from the received signal, including amplitude, phase, and frequency. This markedly enhances spectral efficiency and detection capability.

One of the most notable advantages of coherent detection is an increase in receiver sensitivity of up to 20 dB, as documented in the reference [18]. The extent of this increase is contingent upon the modulation format utilized and the multiplexing mechanisms employed. For instance, sophisticated modulation formats, such as quadrature amplitude modulation (*QAM*) or phase shift keying (*PSK*), can considerably benefit from the capabilities of coherent detection [5,19]. Furthermore, coherent detection mitigates the impact of nonlinear effects within the optical fiber. This is made possible by the complex photodiode system's nonlinear response, which enables more effective management and correction of nonlinear distortions that can impact data transmission at high speeds and over long distances. Mitigating nonlinear effects results in cleaner and more efficient transmission, enabling a longer range and superior signal quality.

Coherent detection also enables a more efficient utilization of the available spectrum in terms of spectral efficiency. The ability to demodulate and detect signals with greater accuracy allows for using narrower channels, thereby increasing the amount of data that can be transmitted per unit of bandwidth. This is particularly significant in high-capacity applications, where bandwidth is a valuable and scarce resource.

Figure 2 illustrates the schematic of the coherent detector, which incorporates a 90° hybrid coupler. This component combines a 2 × 2 coupler with a 90° phase shifter, thereby enabling the combination of the input signal and the local oscillator signal. Because of this combination, two current signals, designated as $i_1(t)$ and $i_2(t)$, are generated. These signals are ideally modeled as a nonlinear response with an intermediate frequency (*IF*). The IF is the difference between the input signal and the local oscillator frequency. This relationship is expressed in Equation (3), where ω_s represents the frequency of the received optical signal and ω_{LO} corresponds to the frequency of the local oscillator [16].

$$\omega_{IF} = \omega_s - \omega_{LO} \tag{3}$$

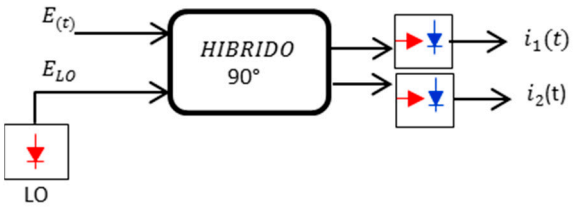


Figure 2. Homodyne coherent detector scheme with a 90° hybrid coupler.

Figure 2 shows the complex envelope of the received signal $E(t)$ and the signal E_{LO}. In Equations (6) and (7), P is the optical power of the input signal, P_{LO} is the optical power of the local oscillator (*LO*), θ_{ns} contains the modulated phase information, and θ_{LO} represents the phase noise generated by the devices.

$$E(t) = Re\{E * e^{j\omega t} * \hat{E}\} \tag{4}$$

$$E_{LO}(t) = Re\{E_{LO} * e^{j\omega t} * \hat{E_{LO}}\} \tag{5}$$

$$E(t) = \sqrt{P} * e^{j(\theta+\theta_{ns})} \tag{6}$$

$$E_{LO}(t) = \sqrt{P_{LO}} * e^{j\omega_{IF}} * e^{j\theta_{LO}} \tag{7}$$

At the output of the 90° hybrid, two current signals are obtained as described in Equation (8), where $\Delta\theta$ is the difference between the noise θ_{ns} and θ_{LO}.

$$i_{12(t)} = \frac{R}{2}\left\{P + P_{LO} \pm 2\sqrt{P * P_{LO}}\sin(\omega_{IF}t + \Delta\theta + \theta) * \hat{E} * \hat{E_{LO}}\right\} \tag{8}$$

where $(P + P_{LO})$ represents the interference between the received signal and the LO reference signal, which can be canceled by electronic domain processing or by balanced coherent detection. Balanced detection results in a current signal described by Equation (10). Balanced detection suppresses the DC component, so the current signal depends on the amplitude and phase of the signal.

$$i_{DE} = i_1(t) - i_2(t) \tag{9}$$

$$i_{DE} = 2R\sqrt{P * P_{LO}}\sin(\omega_{IF}t + \Delta\theta + \theta) * \hat{E} * \hat{E_{LO}} \tag{10}$$

On the other hand, to cancel the phase noise, Equation (11) [20] can be used for the two current signals obtained at the output of the 90° hybrid. This operation improves the signal power.

$$I_o(t) = {i_1}^2(t) + {i_2}^2(t) \tag{11}$$

4. System Design and Implementation

4.1. System Implementation

Figure 3 shows the block diagram of the transmission system, where the dotted blocks represent the Matlab 2018b® tool, while the solid line represents the Optsim 2023.12sp2 simulation tool within the same environment [21].

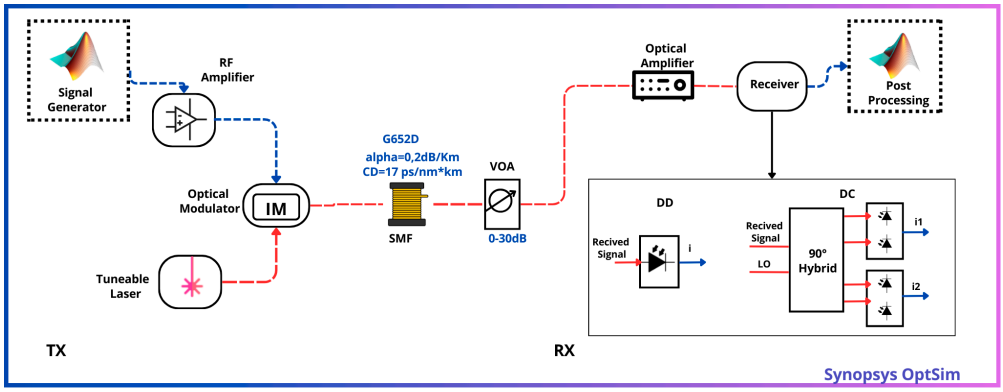


Figure 3. Access network co-simulation configuration with ID-/MM-IDDC SetUp.

The optical transmitter comprises a co-simulation block in Matlab 2018b®, where, in the GFDM signal for the fronthaul link of the 5G network, it is generated through the co-simulation interface with OptSim 2023.12sp2. A vector comprising 10,100 random symbols is created, which is then mapped into a digital modulator to produce a vector $d = [d_0, d_1, \ldots\ldots, d_n\,]$. The 4-QAM and 16-QAM symbols have been optimized for BER of 10^{-3}. The analysis considers an additive white Gaussian noise (*AWGN*) channel, assuming a uniform error probability among the bits. A continuous wave (*CW*) laser source at 1550 nm, with a pulse width of 10 MHz, serves as the optical source, interfacing with the optical distribution network (*ODN)* and functioning as the transmitter. The minimum optical power required for injection is 6 dBm, corresponding to Class C.

The amplified signal was modulated using an intensity modulation and direct or coherent detection (*IM-DD*/*IM-CD*) system. Correctly selecting the bias voltage for the Mach–Zehnder modulator (*MZM*) is essential to ensure its optimal performance. An appropriate bias voltage is critical to avoid signal clipping during the intensity modulation process. In this case, a bias voltage of 2.5V was determined to obtain an adequate BER value, less than 10^{-3} [22].

After modulation, the optical signal was transmitted over a 20 km single-mode fiber (*SMF)* G652D. This fiber has an attenuation of 0.25 dB/km, a dispersion not exceeding 17.0 ps/(nm km), and a polarization mode dispersion (*PMD*) less than or equal to 0.1 ps/$\sqrt{}$km, including the nonlinear effects of the fiber. A variable optical attenuator

(*VOA*) was incorporated into the optical link to simulate variations in the received optical power, especially as the number of users increases. This attenuator allowed the attenuation to vary between 10 dB and 30 dB, corresponding to a received power range of −13 dBm to −30 dBm. This attenuation range is critical for determining BER and EVM under different operating conditions.

The direct detector is configured with a PIN photodiode that exhibits a sensitivity of 0.8 A/W, a dark current of 0.1 nA, and a bandwidth of 10 GHz. In the case of the homodyne coherent detector configuration, an external continuous wave (*CW*) mode laser is employed as the local oscillator (*LO*), in conjunction with a 90° optical hybrid. In this configuration, the local oscillator (LO) and the received carrier are set to a zero-phase shift; that is, the LO laser frequency is tuned to the same frequency as the transmitter, at 193.41 terahertz (*THz*), with an optical power of 6-decibel milliwatts (*dBm*) and a pulse width of 10 megahertz (*MHz),* matching the transmitter values. The coherent detector with a 90° hybrid comprises four PIN photodiodes, each with specifications of 0.8 A/W, 0.1 nA, and 10 GHz, in conjunction with an ideal phase conjugator that mixes the received optical signal with the local oscillator signal with an offset of 90°.

The electrical signal recovered in both detection schemes is processed in Matlab 2018b®, where demodulation is performed to recover the transmitted bits. In this process, the signal power is normalized, the offset voltage is eliminated, Butterworth low-pass filters are applied, and an equalizer is incorporated for the GFMD signal. This results in an improvement in the quality of the recovered signal and the optimization of system performance. Moreover, the two currents obtained at the output of the coherent detector are combined into a single current using Equation (11) before proceeding with the post-processing above.

4.2. Limitations of the System

While a reduction in the optical power necessary to achieve specific BER levels by the GPON standard has been attained, several limitations warrant consideration. Primarily, the system's intricacy is significantly greater than that of the direct detection, necessitating sophisticated equipment such as local, stable lasers and specialized modulators, thereby increasing operational complexity. Furthermore, the financial burden associated with coherent detection is considerable, largely due to the necessity for specialized equipment and DSP, which can also result in latency and increased power consumption. Local laser phase stability and noise have the potential to negatively impact signal quality, while sensitivity to fluctuations in signal polarization introduces an additional challenge [22]. Coherent detection systems necessitate precise frequency alignment between the received signal and the local laser to prevent misinterpretation. Compatibility with existing technologies can be complex and costly, and although DSP helps mitigate chromatic dispersion and other nonlinear effects, these extreme conditions still present significant challenges. These limitations underscore the necessity for developing technical and economical solutions to optimize coherent detection performance in practical applications.

5. Performance Evaluation

As illustrated in Figure 4a, both detection techniques demonstrate an impressive ability to achieve a remarkably low BER of 10^{-4}. However, coherent detection exhibits a distinct advantage in requiring approximately 3 dB less received power to achieve a BER of 10^{-3} ompared to direct detection, as evidenced by a leftward shift in receiver sensitivity. This advantage can be attributed to the ability of the coherent receiver to combine the received signal with the local oscillator power in a 90° hybrid detector, complemented by more sophisticated signal processing. The enhanced sensitivity attained with coherent detection is particularly pertinent in high-speed optical communication applications, where it is crucial to sustain consistent performance under high attenuation conditions. However, to reinforce and contextualize these findings, it is vital to juxtapose them with recent studies that have showcased improvements in receiver sensitivity through advanced techniques,

such as digital dispersion compensation and the deployment of high-efficiency modulators. These emerging technologies could offer further insights to optimize coherent detection in high-demand environments.

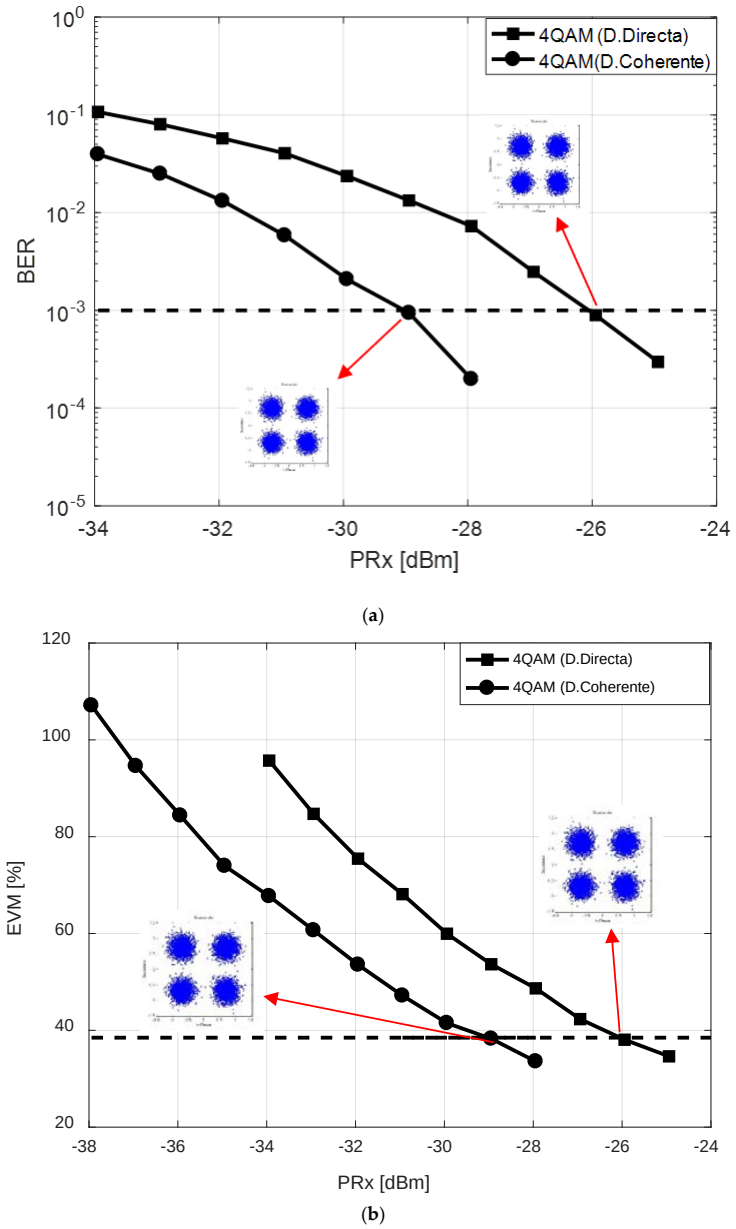
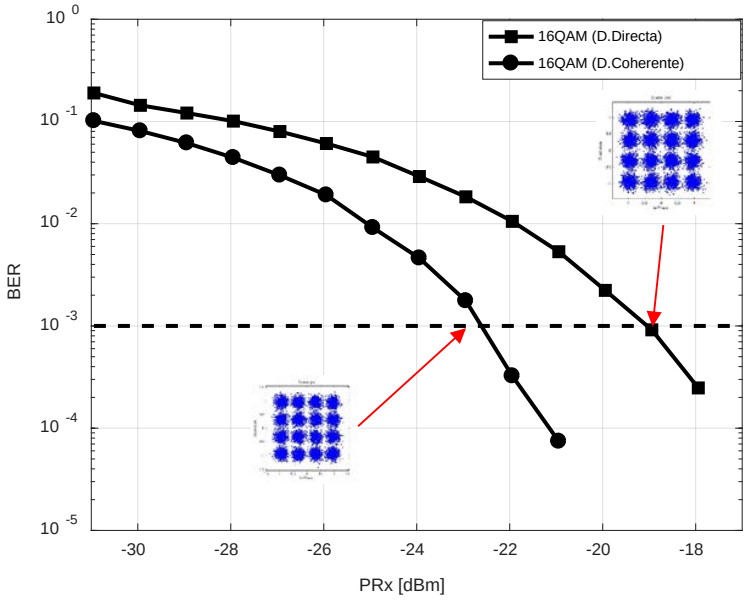


Figure 4. (**a**) Characteristic curves of BER vs. received power. (**b**) Characteristic curves of EVM vs. received power IM-DD/IM-CD for 4 QAM.

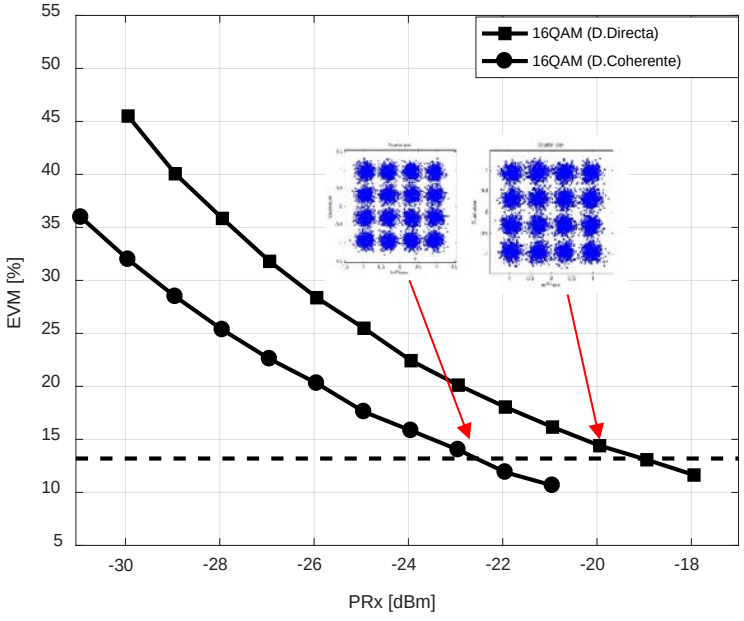
The network performance was evaluated by EVM, for four QAM, where coherent detection requires a minimum receiver power of -29 dBm to achieve an EVM of 28%, corresponding to a BER of 10^{-3} indicated by the dotted line in Figure 4a. This represents a 3 dB improvement over direct detection, which requires at least −26 dBm at the receiver to achieve the same EVM threshold in Figure 4b. The results highlight the significant advantage of coherent detection regarding signal sensitivity and accuracy. The ability of coherent detection to operate with higher signal attenuation without compromising transmission quality is essential for optimizing performance in high-speed, long-haul optical communications systems.

A comparative analysis of BER and EVM curves as a function of received power was conducted for the 16-QAM modulated signal. The findings are presented in Figure 5a. The

results indicate that the highest receiver sensitivity is achieved when a coherent detector is employed. To achieve a BER of 10^{-3}, the receiver sensitivity with coherent detection is approximately -23 dBm, whereas direct detection necessitates a received power of -19 dBm. The 4 dB discrepancy between these methods, as illustrated in Figure 5a, highlights the superiority of coherent detection. Moreover, the examination of the EVM curve regarding received power, illustrated in Figure 5b, demonstrates comparable results. The superior performance of the coherent detector, which requires less received power to maintain a BER of 10^{-3}, is confirmed. It is crucial to acknowledge that the penalty associated with employing a non-coherent receiver compared to a coherent one is approximately 3 dB. This implies that a non-coherent receiver necessitates 3 dB more power to attain the same BER. This underscores the significant benefit of coherent detection in systems where received efficiency is of paramount importance.



(**a**)



(**b**)

Figure 5. (**a**) Characteristic curves of BER vs. received power (**b**) Characteristic curves of EVM vs. received power; IM-DD/IM-CD for 16 QAM.

The analysis additionally encompasses the 5G optical fronthaul link, wherein enhanced performance was discerned by deploying a coherent detector. The system achieved the targeted BER of 10^{-3} with a reduced received power of approximately -29 dBm, which met the specified performance criteria. In this analysis, it is assumed that there is a loss of 0.2 dB per kilometer over 20 km for the GFDM signal. These findings reinforce the superiority of the proposed coherent receiver, particularly in the context of 4QAM and 16QAM schemes, concerning the requisite received signal power. The performance of a 5G fronthaul optical link was evaluated using coherent detectors, demonstrating a notable enhancement in comparison to non-coherent detectors. The results show that a BER of 10^{-3} was attained with an approximate received power of -29 dBm, which exceeded the performance requirements established by the ITU-T G.948.2 standard, which is -26 dBm using an OOK signal in this standard.

6. Conclusions

In conclusion, this study comprehensively compares direct and coherent detection schemes in PONs, demonstrating that coherent detection exhibits superior performance for 4QAM and 16QAM signals. The results demonstrated that coherent detection exhibited approximately 3 dB higher sensitivity than direct detection, consistent with the ITU-T G.948.2 PON specifications. The implementation of GFDM modulation and signal post-processing has been demonstrated to enhance the spectral efficiency and system capacity compared to traditional OOK systems. Notwithstanding the elevated complexity and cost associated with coherent technology, its capacity to maintain a BER of less than 10^{-4} and achieve acceptable EVM levels underscores its effectiveness in advanced optical communications. Moreover, while 4QAM requires less power and is less susceptible to distortion, 16QAM offers twice the information capacity, and coherent detection achieves a more favorable sensitivity penalty compared to direct detection. In conclusion, the results demonstrate the robustness and efficiency of coherent detection in high-speed optical communications, making it the preferred choice for next-generation fronthaul networks, provided that cost and complexity issues can be effectively addressed.

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