OPTOELECTRONICS LETTERS Vol.14 No.5, 1 September 2018

Coherent quadrature phase shift keying optical communication systems

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(Received 4 March 2018; Revised 9 April 2018)

Coherent optical fiber communications for data rates of 100 Gbit/s and beyond have recently been studied extensively because high sensitivity of coherent receivers could extend the transmission distance. Spectrally efficient modulation techniques such as *M*-ary phase shift keying (PSK) can be employed for coherent optical links. The integration of multi-level modulation formats based on coherent technologies with wavelength-division multiplexed (WDM) systems is vital to meet the aggregate bandwidth demand. This paper reviews coherent quadrature PSK (QPSK) systems to scale the network capacity and maximum reach of coherent optical communication systems to accommodate traffic growth.

Document code: A **Article ID:** 1673-1905(2018)05-0372-4

DOI https://doi.org/10.1007/s11801-018-8032-y

The increase in the transmission capacity of wavelength-division multiplexed (WDM) systems has resulted great interest in multi-level modulation formats based on coherent technologies to meet the ever-increasing bandwidth demand[1-4]. Coherent optical communication systems have great prospective for upgrading the capacity of currently deployed optical fiber links. The demonstration of digital carrier phase estimation in coherent receivers has resulted in great interest in coherent optical communications[2]. Spectrally efficient modulation techniques known from wired or wireless communication systems such as *M*-ary phase shift keying (PSK), quadrature amplitude modulation (QAM) and coherent optical orthogonal frequency division multiplexing (CO-OFDM) can be employed for coherent optical links[5,6].

Modulation formats with k bits of information per symbol can achieve a spectral efficiency of up to k bit/s/Hz/polarization compared with 1 bit/s/Hz/polarization for binary modulation formats. For instance, modulation formats with 2 bits of information per symbol such as QPSK can realize up to 2 bit/s/Hz/polarization of spectral efficiency using half the symbol rate while keeping the bit rate. The reduced symbol rate offers numerous gains with regard to tolerance to chromatic dispersion and polarization-mode dispersion (PMD). Moreover, since the phase information is preserved after detection, linear equalization methods can be used to compensate linear optical impairments, such as chromatic dispersion and PMD. In addition, advanced forward error correction (FEC) techniques can be applied to increase reach and robustness of optical communication systems. These aforementioned advantages of coherent links have a great potential to revolutionize current optical communication systems[3,7].

Phase and polarization diverse digital coherent receivers have the potential to increase the capacity of current optical fiber networks, where all four optical carrier dimensions (the in-phase and quadrature-phase components of two orthogonal polarizations) are used for modulation[8,9]. Quadrature phase-shift keying (QPSK) modulation/demodulation research employing optical IQ modulation (IQM) and optical delay detection has been demonstrated, where the bit rate was doubled while maintaining the symbol rate[10]. 100-Gbit/s transmission systems employing QPSK modulation, polarization-division multiplexing at a symbol rate of 25 GBd, have recently been demonstrated and deployed in commercial networks[11].

The recent development of high-speed digital signal processing (DSP) has offered a simple and efficient means for estimating the optical carrier phase by retrieving the IQ components of the complex amplitude of the carrier from the homodyne detected signal[12,13]. This concept was demonstrated in Ref.[14], where a 20-Gbit/s QPSK signal was demodulated with a phase-diversity homodyne receiver followed by digital carrier-phase estimation. DSP improves system stability significantly as compared with the optical phased locked loop (OPLL) scheme[1]. Thus the integration of coherent detection and DSP has become a key part of the next generation of optical communication systems.

The post signal-processing feature of the digital coherent receiver where the IQ demodulation is a linear process is a major advantage. All the information on the complex amplitude of the optical signal is maintained

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even after detection[15,16]. Thus filtering and dispersion compensation can be performed in the electrical domain after detection. Hence dispersion compensated fiber can be excluded.

Moreover, polarization alignment can be achieved after detection as demonstrated by the polarization diversity scheme employed in the homodyne receiver[17,18]. DSP can be used to compute and handle the complex amplitude of both horizontal and vertical polarizations concurrently. Therefore, polarization demultiplexing and compensation for PMD can be achieved, hence eliminating the need for optical-polarization controllers and optical delay lines[8].

The integration of multi-level modulation formats based on coherent technologies with WDM systems is vital to meet the aggregate bandwidth demand. Among various modulation formats, QPSK is the most promising because of its superior transmission characteristics[1]. The main focus of this work is investigating QPSK modulation format to improve the performance and increase the capacity and reach of current optical communication systems efficiently[9,19-21].

The performance of a higher order modulation system can be evaluated by measuring the symbol error rate (*SER*) or bit error rate (*BER*) over a range of background noise, defined as *Eb/No* (the ratio of energy per bit to noise density) or *Es/No* (the ratio of energy per symbol to noise density). For the QPSK format, the *SER* is given by $SER \approx erfc\left(\sqrt{Es/2No}\right)$, while the *BER* is given by $BER=\frac{1}{2}erfc\left(\sqrt{Eb/No}\right)$. For the BPSK format, $SER=BER=\frac{1}{2}erfc\left(\sqrt{Eb/No}\right)$.

A simple system for generating QPSK/BPSK transmission, adding white Gaussian noise and decoding the received symbol for various *Es/No* and *Eb/No* values, was built using the Optisystem tool from Optiwave. The variations of *SER* with *Es/No* and *BER* with *Eb/No* for both QPSK and BPSK schemes are shown in Fig.1 and Fig.2, respectively.

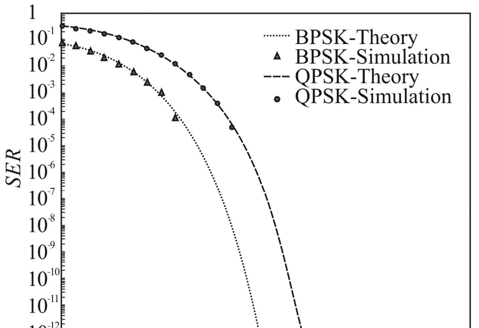

Fig.1 *SER* versus *Es/No*

It is clear from the results that there is a good agreement between the simulated and theoretical plots. Moreover, the QPSK and BPSK have similar *BER* performance. However, in order to achieve the same *SER* as BPSK, the QPSK modulation needs twice the same power (3 dB) because two bits are transmitted simultaneously.

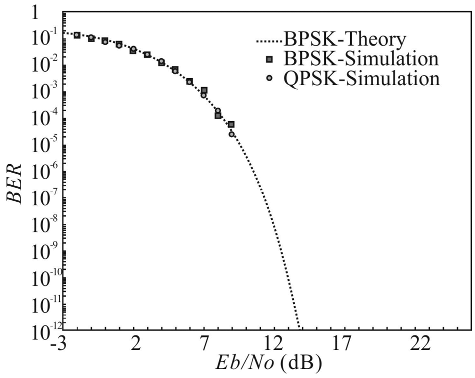

Fig.2 *BER* versus *Eb/No*

Firstly, the quantum noise limit of an ideal homodyne balanced receiver employing QPSK modulation is investigated. The outline of the phase-diversity homodyne receiver is shown in Fig.3. The system was simulated using the Optisystem tool. The following parameters are used in the simulation: bit rate is R_b=10 Gbit/s, symbol rate is R_s=5 Gbit/s, optical carrier frequency is f=193.414 THz, local oscillator frequency is f_{LO}=193.414 THz, and the power of local oscillator is P_{LO}=20 mW. The PIN responsivity R is given by $R=\eta q/hf\approx1.25$ A/W, assuming that the quantum efficiency of photodetector is $\eta=1$ and the dark current is 0 nA. The shot noise of the balanced detector (for each arm) is dominated by the local oscillator power and is given by $\sigma^2=qRP_{LO}B=10^{-11}$ A^2, where B is the bandwidth of the photodiode ($B=R_b/2$).

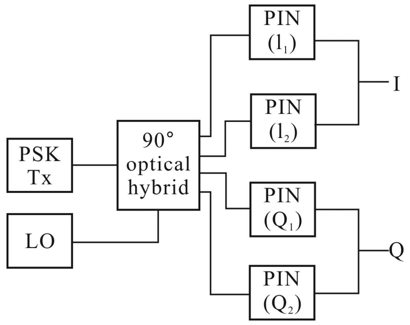

Fig.3 Homodyne balanced receiver

The receiver sensitivity is degraded by 3 dB compared to the BPSK homodyne detection. This is because of the 90° optical hybrid, which results in a 3 dB drop to the input optical signal. Therefore, to achieve the same *BER* of 10^{-9}, the number of photons per bit must be doubled compared with the BPSK, or equal to 18. The *BER* for QPSK homodyne receiver is given by $BER=\frac{1}{2}erfc\left(\sqrt{N_p}\right)$ and that for BPSK homodyne detection is given by $BER=\frac{1}{2}erfc\left(\sqrt{2N_p}\right)$, where N_p is the number of photons per bit[1,22].

Secondly, the quantum noise limit of a synchronous heterodyne QPSK balanced receiver is investigated. Fig.4 shows a schematic of the heterodyne QPSK balanced receiver. The following parameters are used in the simulation: bit rate is R_b=10 Gbit/s, symbol rate is Rs=5 Gbit/s, optical carrier frequency is f=193.414 THz, frequency of local oscillator is f_{LO}=193.434 THz, and the power of local oscillator is P_{LO}=10 mW. The PIN responsivity R is given by $R=\eta q/hf\approx1.25$ A/W, assuming that η=1 and the dark current is 0 nA.

For a *BER* of 10^{-9}, the number of photons per bit must equal 18, where the *BER* is given by $BER=\frac{1}{2}\exp(\sqrt{N_p})$. This is identical to the QPSK homodyne and BPSK heterodyne receiver models, where the *BER* is given by $BER=\frac{1}{2}erfc\left(\sqrt{N_p}\right)$. For the QPSK homodyne receiver, the noise penalty is 3 dB less but the requirement to use a 90° optical hybrid results in a 3 dB signal penalty thus resulting in similar performance compared to the QPSK heterodyne receiver. The performance of the QPSK heterodyne receiver is similar to that of the BPSK heterodyne receiver, as the QPSK symbol occupies two bit intervals and hence has the same number of photons per bit.

The variations of *BER* with the average number of photons per received bit for QPSK homodyne, QPSK heterodyne, BPSK homodyne and BPSK heterodyne receivers are shown in Fig.5. It is clear that there is a good agreement between the theoretical and simulation results. The results show that the heterodyne receiver models have the same performance. This can be explained by the fact that the noise penalty is 3 dB less for QPSK homodyne but this benefit is offset from the need to use a 90° optical hybrid that introduces a 3 dB power loss.

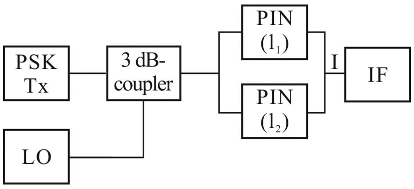

Fig.4 Heterodyne balanced receiver

Fig.6 shows the schematic of a coherent WDM dual polarization QPSK (DP-QPSK) system. The optical DP-QPSK transmitter generates the 112 Gbit/s DP-QPSK signal, where polarization multiplexing is used.

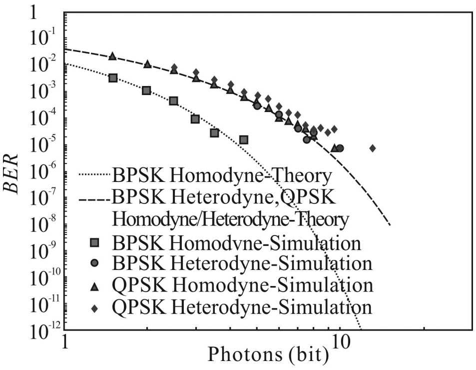

Fig.5 *BER* versus photons number

The 1 550 nm optical carrier signal generated by a CW laser is split into two orthogonal polarization components, which are modulated separately by QPSK modulators and then combined using a polarization beam splitter (PBS). The modulated DP-QPSK signal is multiplexed by the 8×1 AWG at the transmitter and transmitted over the multi spans made up of 80 km single-mode fiber (SMF), followed by erbium doped fiber amplifier (EDFA). At the receiver, the DP-QPSK signal is de-multiplexed by the 1×8 AWG and received by the optical coherent DP-QPSK receiver, which consists of a homodyne receiver design. The receiver has a local oscillator (LO) laser polarized at 45° relative to the polarization beam splitter, and the received signal is separately demodulated by each LO component using two single polarization PSK receivers. Then the output of the DP-QPSK is fed to the DSP. The DSP component performs digital domain impairment compensation such as dispersion compensation and adaptive equalization to aid in recovering the incoming transmission signal after coherent detection.

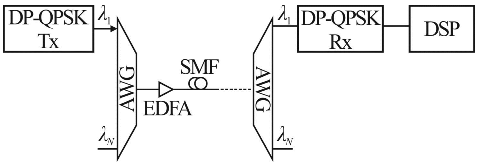

Fig.6 Coherent WDM DP-QPSK system

The variation of *BER* with the optical signal-to-noise ratio (*OSNR*) at back-to-back (B-T-B) and after 160 km SMF and the corresponding constellation diagrams of the 112 Gbit/s DP-QPSK modulated signals are shown in Fig.7. The results show that the *BER* decreases with the increase of *OSNR*. Moreover, they show clear constellation diagrams, which indicates that error free transmission can be achieved. Furthermore, the power penalty is negligible as the *BER* results are very close to those of the back to back case.

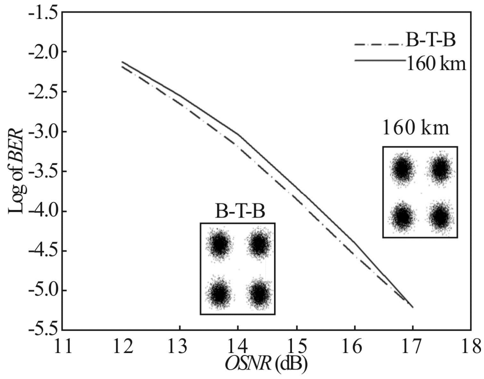

Fig.7 *BER* versus *OSNR*

We have investigated coherent optical communication systems based on QPSK modulation formats. The receiver sensitivities for both homodyne and heterodyne balanced receivers employing QPSK modulation have been analyzed. The simulation results indicate that both QPSK homodyne and heterodyne balanced receivers have similar performance and confirm the theoretical results. Furthermore, coherent WDM dual polarization DP-QPSK system has been investigated. The results show that this scheme is a practical solution for next generation of coherent optical communication systems.

Acknowledgement

The author would like to acknowledge the Alexander von Humboldt Foundation for their support.

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