Comparison of Kramers–Kronig and coherent receivers for few-mode long-haul optical transmission

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ABSTRACT

The nonlinear effects in single-mode fiber and the constraints in device technology, time division multiplexing and wavelength division multiplexing cannot increase the capacity of optical fiber communication system unlimitedly. The development of space division multiplexing technology has increased the capacity of existing optical fiber communication systems by at least an order of magnitude. With the continuous improvement of transmission rate and system bandwidth in the long-haul communication, low cost and small size are also regarded as important factors in the future. In this work, the transmission performance of the low-cost self-coherent receiver and the mature coherent receiver in the long-haul mode division multiplexing system is compared. In the 32-Gbaud 6-mode dual-polarization QPSK transmission system with a fiber length of 80 km as the single span, two receiver schemes are compared considering the same configurations of the transmitter and the optical fiber link components. Compared the use of eight photodetectors integrated in the coherent receiver, the Kramers–Kronig (KK) receiver only requires two photodetectors to demodulate the dual-polarization transmission, while the phase recovery algorithm based on Hilbert transform in the KK receiver will increase the complexity of digital signal processing. Numerical results indicate that the KK receiver scheme has the advantages of lower cost and more compact size, and shows the similar performance as the coherent receiver for the transmission of less than 2500 km, despite the requirement of larger transmitted power and algorithm complexity. It can also be concluded that, self-coherent receiver based on the KK algorithm can be a complementary detection solution to the coherent receiver for next-generation long-haul transmission networks with low-cost transceivers.

Keywords: space division multiplexing, long-haul, self-coherent receiver, few-mode, low cost

INTRODUCTION

In recent years, the rapid advances of emerging broadband access technologies result in the explosive growth of optical information traffic in the short-to-medium range, which covers data center networks, access networks and metropolitan area networks[1]. Short-to-medium range e.g. data center metro traffic has surpassed long-haul traffic. The direct detection scheme is the main commercial solution in short-range scenarios due to the advantage of simple structure and low implementation cost[2,3], but the transmission distance and the signal speed are significantly limited by the thermal noise limit of PD and the low detection dimension[4,5]. With the successful application in long range such as the backbone network communications, the coherent detection technology begins to be applied into short-to-medium scenarios, and simplified coherent detection system is under wide investigations by reducing the complexity and cost[6]. Single sideband self-coherence detection based on the Kramers-Kronig (KK) field reconstruction algorithm is a promising solution due to its high spectral efficiency and excellent signal-signal beat interference (SSBI) cancellation performance[7-9].

After the KK scheme was proposed, it attracted a large number of scholars to conduct in-depth research on it[10-12]. In recent years, researchers have carried out a series of studies on the KK self-coherent receiver, mainly from two aspects: reducing carrier-to-signal power ratio (CSPR) and further improving spectral efficiency under the premise of ensuring the effectiveness of SSBI elimination algorithm. From the perspective of reducing CSPR, the KK receiver scheme based on the exponential operation was proposed in 2019[13], which reduced the CSPR demand by 2 dB in the scenario of 40 km single-mode fiber transmission. Wang et al. optimized the recovered DC offset level in the AC-coupled photodiode KK

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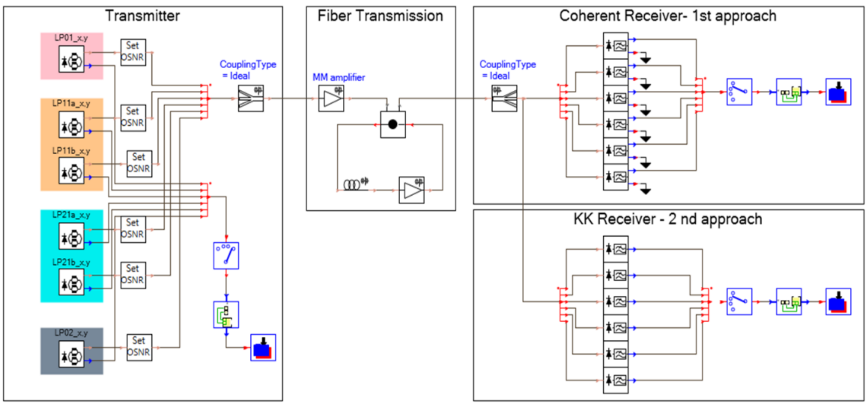
receiver and the optimal digital CSPR was about 2 dB lower than the optical CSPR at a higher optical CSPR regime[14]. From the perspective of improving the spectral efficiency, a novel D-SSB KK receiver using time-slot coding was proposed to eliminate the interference between the two sidebands[15]. The spectral efficiency can be improved to twice the conventional SSB system.

However, as traffic demand of data centers continues to increase, single-mode fiber systems are now approaching their nonlinear capacity limits. In addition to continuing to optimize the device process on single-mode fibers and exploring new technologies to break the Shannon limit, space-division multiplexing (SDM) using few-mode fibers has been reported as an effective approach to improve the transmission capacity[16-18]. Mode division multiplexing (MDM) system can increase transmission capacity and reduce the system cost because of using the more space dimensions, lower signal powers and higher efficiency of optical amplifiers, thus, it is easier to achieve the integration[19,20]. Therefore, MDM system significantly reduces the energy consumption of per bit in the short-to-medium range transmission. When MDM systems introduced into *n*-mode, K-K receiver only requires *n* single photodetectors (PD) and *n* ADC channels while traditional coherent receiver needs 4**n* photodetectors, *n*/2 90◦ optical hybrids and 2**n* ADC channels. Considering that, MDM system combined with KK reception can improve the system transmission capacity and significantly reduce the system total power consumption and cost.

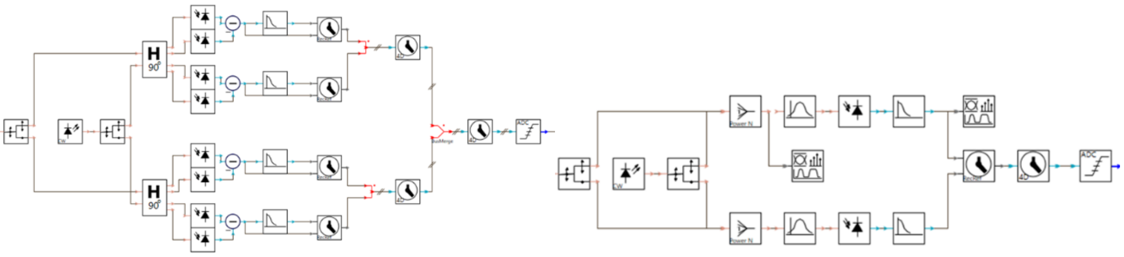
In this paper, we propose and compare the transmission performance of 32-Gbaud 6-mode dual-polarization (DP) QPSK system over 80-km few-mode fiber (FMF) based on mature coherent receiver and simplified self-coherent KK receiver. To the best of our knowledge, this is the first comparative numerical simulations of long-haul MDM system with coherent and KK receivers based on the same configurations of the transmitter and optical fiber link components. The BERs for the transmission of less than 2500 km behave similarly for the KK receiver and the coherent receiver schemes. Admittedly in the KK receiver, higher carrier signal power and frequency offset are required. However, as a trade-off, the KK reception is a promising solution in high-capacity short-to-medium links.

SIMULATION SETUP

Six-mode long-haul transmission simulations are carried out to compare the system performance of the KK and the coherent receiver schemes. Fig. 1(a) shows the simulation setup which is carried out utilizing VPI Design Suite 10.0. The transmission system is simulated using the designed transmitter, six-mode fiber, few-mode amplifier, mode multiplexer, demultiplexer and coherent receiver modules in the VPI as well as the self-built integrated KK receiver module. The internal details of the coherent receiver designed by the VPI software and the self-built integrated KK receiver are shown in Fig. 1(b) and (c). At the transmitter part, the bit sequence is mapped into 2^{23}-1 QPSK symbols with 32-Gbaud symbol rate and up-sampled by a factor of 8. The signal then passes through a root-raised-cosine (RRC) pulse shaping filter with a roll-off factor of 0.1. The continuous wave light is generated by an external cavity laser (ECL) with 100 kHz linewidth at 1550 nm. An OSNR-set module is applied to add depolarized noise to the input signal by setting the specified OSNR. FMF of 80 km with 20 ps/nm/km dispersion coefficient at 1550 nm, 0.2 dB/km attenuation coefficient of LP_{01}, 0.02 dB/km mode-dependent loss is used for transmission.



(a)



(b) (c)

Figure 1. Simulation system of the proposed scheme. (a) Configuration of the 32-Gbaud 6-mode DP-QPSK optical fiber communication system using the coherent or the KK receivers. (b) Schematic of the coherent receiver. (c) Schematic of the coherent receiver.

At the receiver side, the received optical power is adjusted to 0 dBm using the EDFA. In order to ensure the consistency of the comparison between the two receiver schemes, the KK receiver includes a strong carrier signal with a large frequency offset at the receiving side. The detected optical signal is coupled with the added strong carrier signal and then they pass through the 50 GHz bandwidth Gaussian-shaped optical bandpass filter which is used to filter out the out-of-band noise. The filtered signal is detected by a 40 GHz PD with 1.0 A/W responsivity. For the coherent receiver, a local oscillator signal with the same center frequency as the signal is also added to the receiving side. After all these procedures, the received signals of two receivers are followed by an ADC with 4*32 GSa/s sampling rate, 40 GHz bandwidth and are processed by an offline MATLAB program.

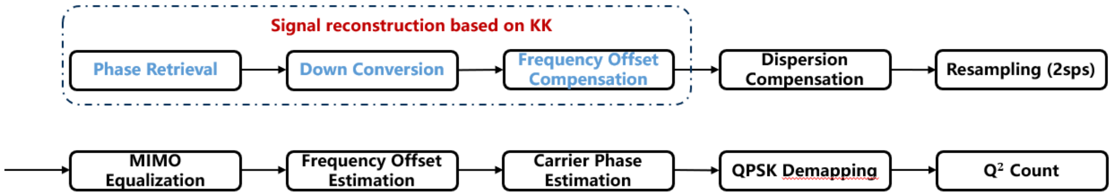


Figure 2. Block diagram of the coherent and KK receiver algorithm.

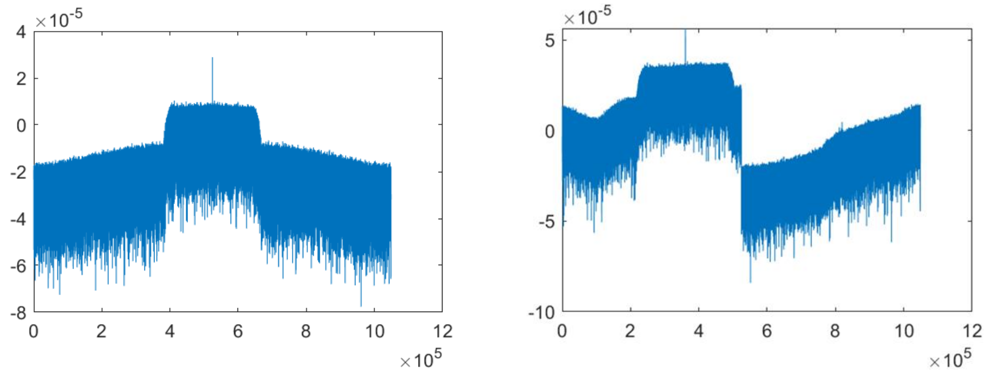
The offline digital signal processing (DSP) algorithm flow is shown in Fig. 2. Since the KK receiver can only detect the intensity information, the phase information needs to be recovered by Hilbert transform in DSP. In order to meet the minimum phase condition, a high-power carrier signal with a large frequency offset is added before the detection, so the down conversion and the frequency offset compensation are required to achieve the correct signal reconstruction. The subsequent DSP process is the same as the coherent receiver, which mainly includes the dispersion compensation, the down-sampling which is used to reduce the complexity of subsequent MIMO equalization, the MIMO equalization based on the recursive least square algorithm, the frequency offset estimation, the carrier phase recovery, the QPSK demapping and calculation of Q^2 value.

Table 1. Parameters and values used in DSP.

Parameter	Value (KK receiver)	Value (KK receiver)
Length of Hilbert transform filter	64	
Length of down conversion filter	64	
Oversampling rate	4	4
Numbers of convergence	2~4	2~4
Required tap length of equalizer	256~8192	256~8192
Step sizes of convergence	10	0.01
Length of training sequence	200000	200000
forgetting factor	0.99	0.99

Table 1 shows the detailed parameters and values of offline DSP for the two receiver schemes. The number of taps and equalization times will gradually increase with the transmission distance. Since the KK receiver needs to recover the full-field information of the signal in DSP, the algorithm additionally performs the Hilbert transform to recover the phase information and the down-conversion to recover the intermediate frequency signal compared with the coherent receiver. Thus the algorithm complexity based on KK receiver is higher.

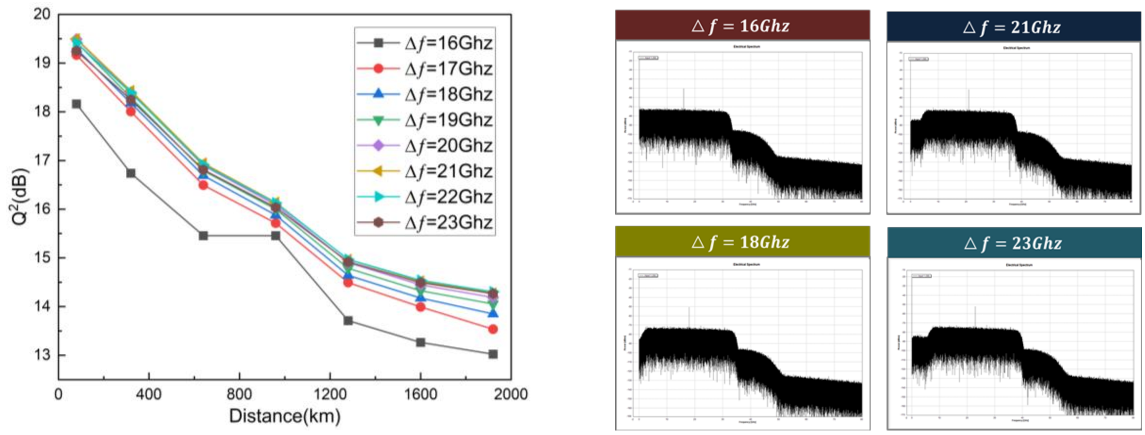
RESULTS AND ANALYSIS



(a) (b)

Figure 3. (a). Signal spectrum before dispersion compensation in coherent receiver (b). Signal spectrum before dispersion compensation in KK receiver.

The spectra of the detected signals before the dispersion processing for the two receiver schemes are illustrated in Fig. 3. Compared with the KK receiver using two photodetectors, the coherent receiver involves more high-cost devices, but it keeps the complete amplitude and phase information of signal through the beating frequency between the local oscillator and received signal, matching the results in Fig. 3(a). The middle flat area in the signal spectrum in Fig. 3(b) is the QPSK signal transmission. Since the KK self-coherent receiver realizes the recovery of the phase information based on Hilbert algorithm, which involves some nonlinear operations and the addition of a carrier with large frequency offset, the detected signal spectrum has a certain frequency offset, which needs to be down-converted in the subsequent algorithm.



(a) (b)

Figure 4. (a) Q^2 performance vs distance of KK receiver under different frequency offsets (b) the electrical spectrum of the electrical filter after the photodetector under different frequency offsets

The perfect field reconstruction of KK receiver needs to meet the minimum phase condition, so it involves two important parameters: the frequency offset and the CSPR. Aiming at the two important parameters, their influences on the system transmission results are studied. Firstly, the relationship between the Q^2 factor and the distance at different frequency offset values is studied. In order to meet the strong carrier signal, the CSPR is set as 12 dB. The symbol rate of the transmitted signal in the system is set as 32-Gbaud and the roll-off coefficient is 0.1. Theoretically, when the frequency offset exceeds 17.6 GHz, the minimum phase condition of single sideband signal is met. It can also be seen from the Fig. 4(b) that when the frequency offset is less than the signal bandwidth, such as the frequency offset of 16 GHz. The electrical spectrum of the electrical filter after the photodetector can be observed that the information in part of the bandwidth is lost, and the single sideband signal condition is violated. With the increase of the frequency offset, when it exceeds the bandwidth, the Q^2 factor gradually increases, and the transmission effect is improved. As the frequency offset gradually increases, more amplified spontaneous emission (ASE) noise is introduced between the strong carrier and the signal, and the OSNR decreases. This also gradually breaks the minimum phase condition, as shown in Fig. 4(b) with a frequency offset of 23 GHz. Therefore, considering the transmission quality and the spectral efficiency comprehensively, the frequency offset is set as 20 GHz for the subsequent research on the CSPR parameter.

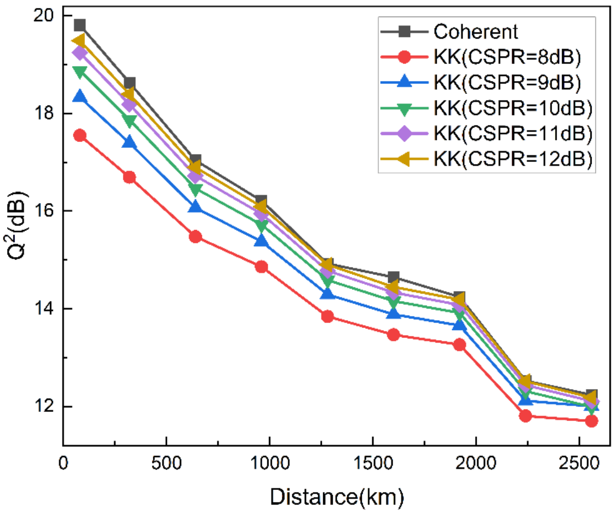
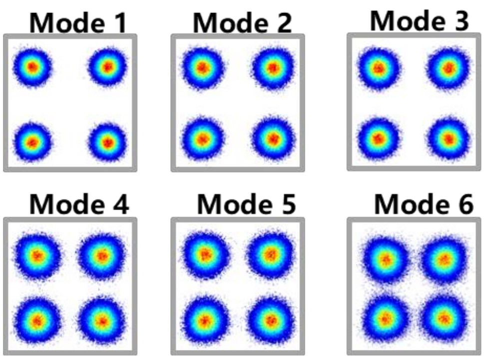


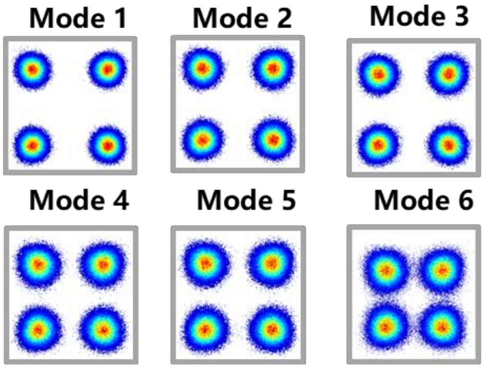
Figure 5. Averaged Q^2 vs. transmission distance with coherent and KK receivers

In order to compare the transmission performance of the two receiver schemes under the same simulation conditions, the detected signal power is set as 0 dBm, and the power of the local oscillator in the coherent receiver is set as 5 dBm, which can be considered as a CSPR of 5 dB. The frequency offset is set as 20 GHz to get the optimum system performance and the power of strong carrier signal added in the KK receiver depends on the value of CSPR. Fig. 5 shows that the transmission effect is gradually improved in the KK receiver with the increase of CSPR. When CSPR is small, the system is affected by ASE noise and the interference from signal and signal beat frequency caused by the direct detection of the detector, resulting in poor transmission effect. With the larger CSPR, the SSBI can be better eliminated and the signal reconstruction can be better carried out. Among them, the transmission performance of the KK receiver at the CSPR of 12 dB is similar to that of the coherent receiver at the CSPR of 5 dB under 2500 km.



BER_x(*1e-3)			
	LP_{01}	LP_{11a}	LP_{11b}
	0.008	0.055	0.093
	LP_{21a}	LP_{21b}	LP_{02}
	1.25	1.242	4.959

(a)



BER_x(*1e-3)			
	LP_{01}	LP_{11a}	LP_{11b}
	0.004	0.046	1.343
	LP_{21a}	LP_{21b}	LP_{02}
	1.469	1.006	6.331

(b)

Figure 6. (a)Constellations and BERs after 2500 km transmission for coherent receiver (b) Constellations and BERs after 2500 km transmission for KK receiver

Fig. 6 provides the constellations and the calculated bit-error rate (BER) of all modes based on the two receivers after the 2500 km transmission. It can be seen that the two receivers have almost the same results. Although the KK receiver requires higher transmitted power and algorithm complexity, considering the lower cost and the size requirement of future transmission systems, KK receiver is a good potential alternative to coherent receiver.

CONCLUSIONS

We have conducted a comparative study between the conventional coherent receiver and the self-coherent KK receiver in the scenario of few-mode long-haul optical transmission. The MDM transmission performance of the two receiver schemes is investigated using numerical simulations. Results show that the Q^2 factor and the BER results calculated the use of the KK receiver with the higher CSPR and frequency offset are similar to the coherent receiver for 32-Gbaud 6-mode dual-polarization QPSK transmission with the distance of less than 2500 km. As a trade-off of cost, size and computational complexity, the KK receiver is a promising solution in high-capacity short-to-medium MDM links.

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