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On the Effect of Receiver Impairments on Incoherent QAM Systems

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Incoherent QAM is a differentially detected, multilevel modulation format that can improve spectral efficiency in optical communication systems. The effect of three receiver impairments on the performance of an incoherent QAM system is assessed in this paper for the first time. Specifically, the impairments studied are an unbalanced Mach-Zehnder Interferometer (MZI), the phase detuning of the MZI and the amplitude imbalance of the Balanced Photodetectors (BPD). Extensive simulations were carried out and results indicate that incoherent QAM is quite robust in respect to the aforementioned impairments, with the phase detuning being the most critical parameter leading to performance degradation

Introduction

Multilevel modulation formats have gathered a considerable amount of attention in the field of optical communication systems [1]. The increased spectral efficiency of multilevel formats and the possibility of electronic compensation of transmission impairments (chromatic and polarization mode dispersion), associated with digital coherent receivers, are the main reasons for this increased interest. The authors have recently proposed the use of Quadrature Amplitude Modulation (QAM) with incoherent detection in a Passive Optical Network (PON) [2]. This approach enables the transmission of 10 Gb/s signals using electronics and optoelectronics operating at 2.5 GHz (with 16QAM).

The increase in spectral efficiency achieved in QAM signals comes at the expense of increasing transceiver complexity. The incoherent QAM receiver comprises of two MZIs, two BPDs and one photodiode. Therefore, it is fundamental to explore the sensitivity of incoherent QAM to possible variations from the optimal values of the most critical parameters of such a complex receiver. The relevant receiver parameters are the couple ratio of the outputs of the MZI, the phase shift in the MZI and the responsivity matching of the BPDs.

An extensive study on the effect of receiver impairments on DQPSK systems has been performed on [3], but to the best of the authors' knowledge, no such study has been performed for higher-order modulation formats, such as QAM. In this paper, the performance degradation of an incoherent 16QAM system resulting from the aforementioned receiver impairments is assessed using simulations.

The remainder of the paper is organized as follows: in Section II, the incoherent QAM transmitter and receiver and the main impairments to the signal are described. In Section III, the simulation set-up is described and results are presented, and finally, Section IV provides some conclusions.

Receiver structure and relevant parameters

Incoherent modulation formats encode the information on the phase difference between consecutive symbols, since an absolute phase reference is not available. The corresponding operation on incoherent QAM is called phase pre-integration (first introduced in optical communications in [4]) and consists of adding the phase of the previous symbol to the current one. The original QAM symbol is denoted as $a_k e^{j\phi_k}$ and the transmitted symbol, therefore, becomes $a_k e^{j(\phi_k + \phi_{k-1})}$. The QAM symbol is then split into its real (I) and imaginary (Q) components and is predistorted, to compensate for the nonlinear transfer function of the MZ modulator. The resulting I and Q optical components in each case are then combined to form the optical QAM signal. The schematic of the QAM transmitter configuration used can be seen in Fig. 1.

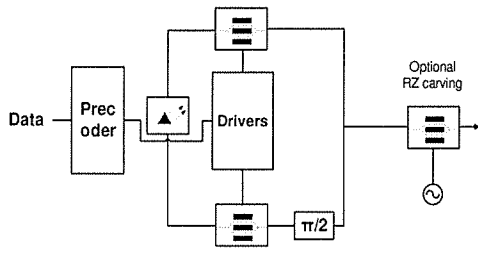


Figure 1 Incoherent QAM transmitter

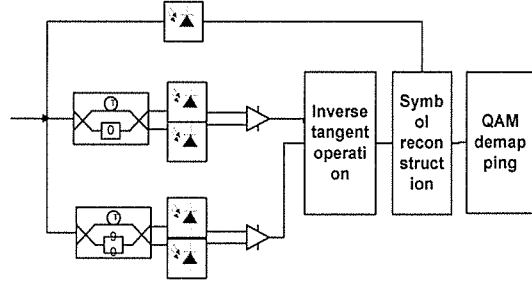


Figure 2 Incoherent QAM receiver

Incoherent modulation formats use interferometric-based demodulation [4]. An interferometric receiver consists of two asymmetric Mach-Zehnder interferometers, followed by two balanced detectors. Each MZ interferometer has a time delay equal to one symbol period and a phase shift of $\theta, \theta - 90^\circ$ respectively, with θ depending on the modulation format. For QAM, a separate photodiode is needed to produce an estimate of the amplitude of the received signal. If the received signal is denoted as $r(t)e^{j\phi(t)} + n(t)$, the outputs of the balanced detectors are:

$$i_1(t) = K_1 \frac{r(t)r(t-T)}{4} \cos[\phi(t) - \phi(t-T) - \theta] + n_1(t)$$

$$i_2(t) = K_2 \frac{r(t)r(t-T)}{4} \cos[\phi(t) - \phi(t-T) - \theta + 90^\circ] + n_2(t)$$

For QAM, $\theta = 0^\circ$ and the output currents are proportional to $\cos \Delta\phi, \sin \Delta\phi$, where $\Delta\phi$ is the phase difference between the current and the previously received symbol. Using these two metrics, the inverse tangent is computed and an estimation of the phase difference is produced, which is an estimation of the phase of the original QAM symbol, before the pre-integration operation. Since amplitude estimation is also available, from the single photodiode, the transmitted symbol can be reconstructed at the receiver. The QAM receiver can be seen in Fig. 2.

The receiver impairments under study can also be seen on Fig. 2. The unbalanced MZI impairment is defined as the deviation of the coupling factor of the two outputs of the MZI from the ideal value (0.5), resulting in uneven optical powers reaching the BPDs. The phase detuning of the MZI is a non-ideal phase shift in one of the MZI, with $\theta \neq 0$.

This detuning can be particularly detrimental on the received signal quality, as it leads to a rotated constellation diagram. Finally, the amplitude imbalance of the outputs of the BPD pairs results from a mismatching of their responsivities, K_1 , K_2 , expressed as $R = \frac{K_1 - K_2}{K_1 + K_2}$.

All these variation from the optimal values can lead to potentially significant degradation of the received signal.

Simulations

The impact of the aforementioned impairments was examined on a 10Gb/s incoherent 16QAM signal, transmitted through 20 km of fiber, in a Passive Optical Network (PON), as the one proposed in [2]. The reason for performing the simulation under such a setting is that incoherent QAM is more suited for access networks, since it does not require an expensive, low-linewidth laser and polarization control, as does coherent QAM. Also, in access networks low-cost devices are desirable, implying that deviations from ideal parameter values need to be tolerated.

The simulation were performed on the VPTransmissionMaker software, with the laser linewidth set to 200 kHz and the received power set to -30 dBm (before optical amplification). The constellation diagram for the ideal receiver is shown in Fig. 3a. To illustrate the effect of the receiver impairments on the signal, the constellation diagrams for certain non-ideal values of the relevant parameters are shown in Fig. 3b-3d. It is clear from the figures that the deviation from the optimal values can severely deteriorate the quality of the received signal, especially for the case of unbalanced MZI and phase detuning.

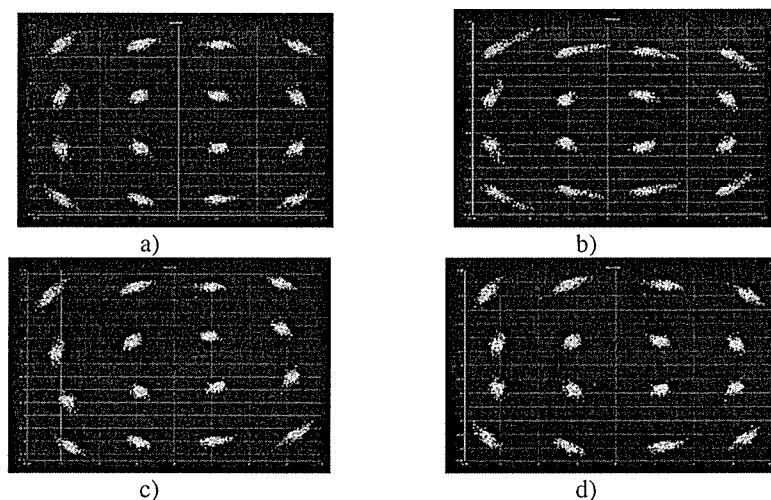


Figure 3 a) Ideal receiver b) Couple ratio 0.42 c) Phase shift 80 degrees d) R 0.12

In order to quantify the effect of the impairments, the Error Vector Magnitude (EVM) of the received signals was measured for a range of the parameter values around the optimal point. EVM is a good indication of the distortion of the received signal, as it measures the distance of the received constellation points from the ideal constellation. In every case, the upper part of the incoherent receiver is set to the nominal values,

while in the lower part the parameter under study is set to the deviated values. The results are shown in Fig. 4a-c. The reference signal has an EVM of 6.8%, resulting to a Bit Error Rate (BER) around 10^{-11} , while an EVM of 15% leads to a BER below the threshold of error-correcting codes (around 10^{-3}). From Fig. 4a, it can be seen that even for a coupling ration of 0.6/0.4, error-free detection can be achieved. For the phase detuning (Fig. 4b), a shift of 10 degrees is the limit for correct detection. Finally, for the responsivities mismatch, a value of R up to +/-0.15 is allowed (Fig. 4c), which means that for reasonable mismatch values, the signal distortion remains low.

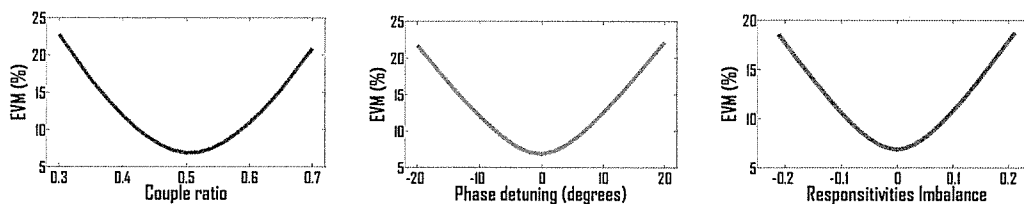


Figure 4 EVM values for a) Couple ratio imbalance b) Phase detuning c) Responsivities imbalance

Conclusions

The effect of receiver impairments on the incoherent QAM modulation formats was examined for the first time. The results indicate that the imbalance of the MZI output coupler and the mismatched BPD responsivities do not significantly degrade the quality of the received signal for reasonable deviations from the optimal values. On the other hand, incoherent QAM is quite sensitive to the detuning of the phase shifts of the MZI, as it results in a rotated constellation diagram. However, this effect can be mitigated by implementing suitable algorithms on the signal processing part of the receiver. In conclusion, simulations show that incoherent QAM signals can achieve error-free transmission (with error correcting codes), even at the presence of significant receiver impairments, relaxing the requirements for the receivers.

Future work will include experiments to validate the results obtained through simulations. Moreover, algorithms that can minimize the effects of the receiver impairments studied in this paper will be explored and their performance will be analyzed.

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