Application Limits of Single-Wavelength Communications by Orthogonal Modulation Formats

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ABSTRACT
The use of orthogonal modulation formats for the transmission of separate data streams over the same wavelength allows an efficient use of fiber infrastructure in any optical network. Particularly, Frequency-Shift Keying (FSK) and Intensity Modulation (IM) can be accomplished very simply by simultaneous direct and external modulation of an optical source giving rise to great cost reduction. However, non-perfect orthogonality between modulation formats leads to interference upon data reception, which has been analyzed. For this purpose, system parameters affecting mutual interference between data streams are identified and its effect quantified in terms of loss of Signal-to-Noise Ratio. Finally, the application of the analyzed scheme to some interesting scenarios is discussed. These scenarios include unidirectional and bidirectional examples, such as labelling in Optical Packet Switched Networks, multiple data-stream transmission in short-range applications such as automotive networks and remote-seeding in Passive Optical Networks. Analytical results presented in this paper are in good agreement with reported experimental results.
Keywords: orthogonal modulations, direct-modulated lasers, crosstalk, adiabatic chirp.

1. INTRODUCTION

The use of orthogonal modulation formats can be applied to a number of scenarios that can benefit from simultaneous transmission of two separate data signals over the same wavelength. Several format combinations have been proposed in the literature, which were originally conceived for labeling in packet-switched networks and subsequently implemented in other scenarios such as passive optical networks. However, perfect orthogonality is hardly achieved due to either or both the implementation of the modulation technique and the effect of transmission over the network fiber links. In this work a simple and cost-effective technique for FSK/IM orthogonal modulating an optical carrier is analyzed in terms of associated crosstalk between data streams. The technique is based on direct and external modulation of a standard optical source. A tradeoff in the choice of the IM extinction ratio is found and factors affecting this tradeoff are discussed and their influence analytically assessed. Application limits of the orthogonal modulation technique depend on the network scenario and the optical source characteristics.

2. NARROW-FSK / IM TRANSMISSION

Combining Frequency Shift Keying (FSK) and Intensity Modulation (IM) formats has some advantages over other approaches, since it avoids the use of external modulators and relaxes the laser linewidth restrictions [1]. Additionally, by performing FSK via direct modulation of the laser source, simplicity and cost can be further increased. The main disadvantage of such modulation technique is the arising of Residual Intensity Modulation (RIM), which will cause interference with the IM-modulated data. Therefore, keeping FSK frequency deviation small is very important since it simultaneously allows for spectrally efficient transmission and RIM reduction. Frequency deviations as small as 0.7 GHz have been reported, being such modulation termed narrow-FSK [2].

FSK/IM modulated signal allows simultaneous transmission of separate data streams according to the following expression for the complex envelope of the optical field $E(t)$

$$E(t) = E_0\sqrt{1+\mu x_1(t)}\cdot \mathrm{e}^{j\left(\omega_0 t + \frac{\Delta\omega_f}{2}\int_{-\infty}^{t} x_2(t)dt\right)} \tag{1}$$

where $x_1(t)$ and $x_2(t)$ are the data signals to be transmitted, μ is the IM modulation depth and $\Delta\omega_f$ the FSK frequency deviation. We assume that both data signals are NRZ with amplitude variation between -1 and 1 and that FSK signal is transmitted at a lower data rate than IM signal. Equation (1) represents the ideal case where no interference between modulations is present so that they are effectively orthogonal. However perfect orthogonality between modulation formats is not found in practice, so that mutual interference affect transmission performance of both data streams.

2.1 FSK to IM interference

Interference caused by FSK-modulated data over IM-modulated data is related to the presence of RIM, which introduces another term in the amplitude of the complex envelope associated to the RIM modulation depth μ_{RIM}. Expressions for the complex envelope and the optical intensity are:

$$E(t) = E_0 \sqrt{1+\mu x_1(t)} \cdot \sqrt{1+\mu_{RIM} x_2(t)} \cdot \mathrm{e}^{j\left(\omega_0 t + \frac{\Delta\omega_f}{2}\int_{-\infty}^{t} x_2(t)dt\right)} \tag{2}$$

$$X(t) = X_0 \left(1+\mu x_1(t)\right) \cdot \left(1+\mu_{RIM} x_2(t)\right) \tag{3}$$

Consequently, crosstalk is lower when RIM is reduced, which is equivalent to reduce RIM modulation depth. Particularly, if we consider high enough data rates so that chirp thermal contribution is very small [3] and we further neglect transient chirp, RIM modulation depth for a given frequency deviation can be expressed as

$$\mu_{RIM} = \frac{1}{2}\frac{\Delta P}{P} = \frac{1}{2}\frac{\frac{4\pi}{\alpha\kappa}\Delta\omega_f}{P} \tag{4}$$

where α and κ are chirp-related parameters of the optical source and P is the average emitted optical power. As already mentioned, RIM reduction can be accomplished by decreasing frequency deviation, but this reduction is limited by transmission rate of data stream $x_2(t)$ and physical restrictions in the demodulation process [4].

2.2 IM to FSK interference

Interference caused by IM-modulated data over FSK-modulated data is related to the spectral overlap which introduces a multilevel structure after the demodulation process. Assuming that the demodulation filter has a transfer function which is linear in the proximity of ω_0 with slope k [5]

$$T(\omega) = 1 + k(\omega - \omega_0)\,, \tag{5}$$

FSK demodulated signal can be written via the complex envelope of the optical field:

$$\begin{aligned} E_{filt}(t) &= E(t) - jk \cdot e^{j\omega_0 t} \cdot \frac{d}{dt}\left(E(t) \cdot e^{-j\omega_0 t}\right) = \\ &= E_0 \cdot e^{j\left(\omega_0 t + \frac{\Delta\omega_f}{2}\int_{-\infty}^{t} x_2(t)dt\right)} \left[\sqrt{1+\mu x_1(t)}\left(1 + k\frac{\Delta\omega_f}{2}x_2(t)\right) - j\frac{\mu k \frac{dx_1(t)}{dt}}{2\sqrt{1+\mu x_1(t)}}\right] \end{aligned} \tag{6}$$

and via the signal optical intensity:

$$X_{filt}(t) = X_{0,filt}\left(1+\mu x_1(t)\right) \cdot \left(1 + n x_2(t)\right) \tag{7}$$

where n is a constant related to the discrimination properties of the filter and the FSK frequency deviation

$$n = \frac{4k\Delta\omega_f}{4 + k^2 \Delta\omega_f^{\,2}} \tag{8}$$

Thus, comparison of equations (3) and (7) leads to conclude that the crosstalk effect of FSK to IM and IM to FSK data streams has a similar behaviour. In the first case interference is controlled by the relative value of the RIM modulation depth μ_{RIM} to the IM modulation depth. In the second case interference is controlled by the relative value of the IM modulation depth to the discrimination constant n of the FSK demodulation filter. Therefore a tradeoff is found in the choice of the IM modulation depth so that high values reduce FSK to IM crosstalk, while low values benefit the reduction of IM to FSK crosstalk.

3. INTERFERENCE IMPACT OVER TRANSMISSION QUALITY

Evaluation of the transmission degradation caused by mutual interference between modulation formats is performed by obtaining the Signal to Interference Ratio (SIR) of each data stream. For doing this, the power spectral density (PSD) of the received signals is first calculated leading to the following expressions:

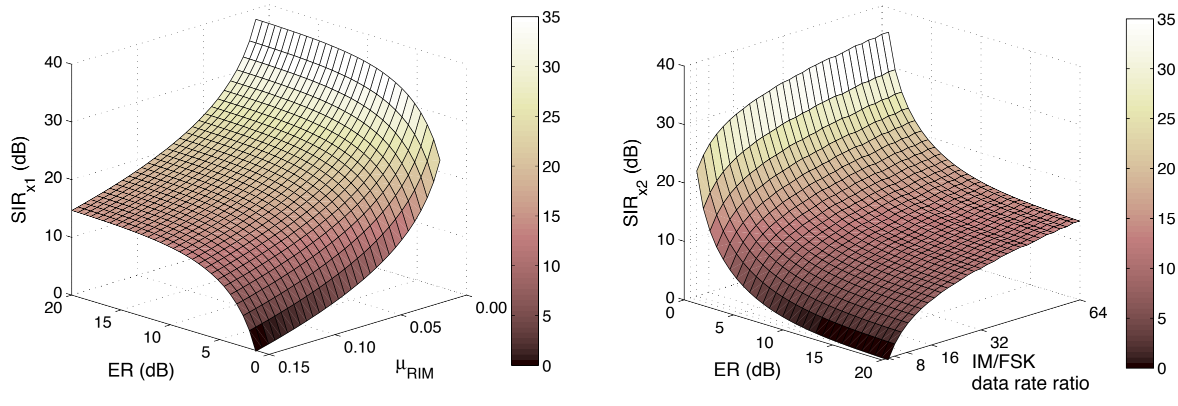
$$\begin{aligned} S(\omega) &= X_0^{\,2} \cdot \left(\delta(\omega) + \mu^2 S_{x_1}(\omega) + \mu_{RIM}^{\,2} S_{x_2}(\omega) + \mu^2 \mu_{RIM}^{\,2} S_{x_1}(\omega) * S_{x_2}(\omega)\right) \\ S_{filt}(\omega) &= X_{0,filt}^{\,2} \cdot \left(\delta(\omega) + n^2 S_{x_2}(\omega) + \mu^2 S_{x_1}(\omega) + n^2\mu^2 S_{x_2}(\omega) * S_{x_1}(\omega)\right) \end{aligned}\,, \tag{9}$$

where $S_{x_1}(\omega)$ and $S_{x_2}(\omega)$ are the PSDs of data signals $x_1(t)$ and $x_2(t)$, respectively. From this, SIR at reception is

$$SIR_{x_1} = \frac{\int_0^{\omega_1} S_{x_1}(\omega)d\omega}{\mu_{RIM}^{\,2}\int_0^{\omega_1}\left(\frac{1}{\mu^2}S_{x_2}(\omega) + S_{x_1}(\omega) * S_{x_2}(\omega)\right)d\omega}, \quad SIR_{x_2} = \frac{\int_0^{\omega_2} S_{x_1}(\omega)d\omega}{\mu^2\int_0^{\omega_2}\left(\frac{1}{n^2}S_{x_1}(\omega) + S_{x_1}(\omega) * S_{x_2}(\omega)\right)d\omega}, \tag{10}$$

where ω_1 and ω_2 are the receiver bandwidth of signals $x_1(t)$ and $x_2(t)$, respectively.

Figures 1 and 2 show the Signal to Interference Ratios of IM-modulated data $x_1(t)$ and FSK-modulated data $x_2(t)$ as a function of IM Extinction Ratio (ER) and either RIM modulation depth or IM to FSK data rate ratio. Receiver bandwidths ω_1 and ω_2 have been assumed to be adjusted to the main lobe of the corresponding PSD, while FSK filter factor n has been assumed to take its maximum value ($n = 1$).

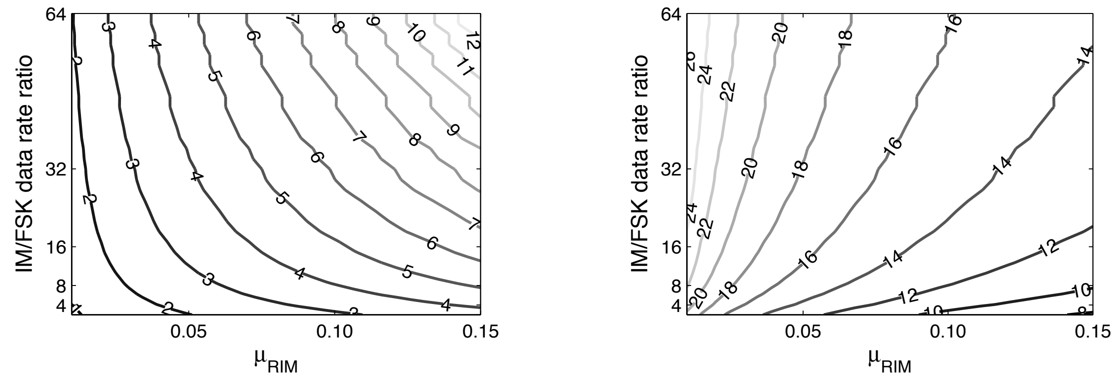


(a) *(b)*

Figure 1. Signal to interference ratios of IM-modulated data (a) and FSK-modulated data (b).

As can be observed from the Figure, the presence of high RIM levels greatly reduces SIR of the IM-modulated data $x_1(t)$ so that a high IM extinction ratio is necessary to guarantee an appropriate data reception. On the other hand, high ER values reduce the SIR of the FSK-modulated data $x_2(t)$. However, by increasing the IM to FSK data rate ratio, transmission quality can be improved, as the spectral overlap is reduced.

The optimum extinction ratio value can be extracted from the above surfaces by calculating their intersection and thus finding the SIR values for which transmission performance of both data streams is equal and thus none of the signals quality is compromised by the presence of the other one. Figure 2 shows the curves for the theoretical optimum values of ER and SIR. From this Figure, particular ER and SIR values for several scenarios can be obtained by just knowing the data rate ratio and RIM modulation depth, which depends on the laser characteristics and FSK frequency deviation according to (4).



(a) *(b)*

Figure 2. Optimum values of extinction ratio (a) and SIR (b). Both magnitudes are expressed in dB.

4. APPLICATION SCENARIOS

The combined modulation scheme can be applied to a number of scenarios which can benefit from a cost-effective simultaneous transmission of two separate data streams using a single wavelength. This is the case of optical packet-switched communication networks in which each packet is routed according to some control information related to that packet. In this case, both data and control field can be attached simultaneously to each particular packet and then be transmitted through the network simultaneously without any strict bit synchronization. Another scenario can be found in passive optical networks based on remote-seeding of the network terminals from the central office. Cost-effectiveness is crucial in this kind of networks, so that they can greatly benefit from the proposed modulation scheme. Finally, orthogonal modulation formats in can be applied to transportation networks found in automotive or avionics environments, which are characterized by a rapid growth of the bandwidth demanded by users and the heterogeneity of services to be provided.

4.1 Optical packet-switched communication networks

In this scenario, orthogonal modulation formats may be used for encoding payload and control data of each packet. Since payload data requires much higher data rate than control data, we propose to IM-modulate the first and FSK-modulate the latter one. Interference between modulation formats has to be taken into account carefully, since it will cause errors upon reception of both data fields.

Experimental bit error rate measurements of FSK/IM transmission performance in this scenario revealed that the best choice of the IM extinction ratio value is 2.5 dB [2]. This result is in good agreement with the analytical value obtained from the curves in Figure 2 when the actual experimental setup conditions are considered, i.e., data rate ratio of 4 and RIM modulation depth of 8%.

4.2 Colorless passive optical networks

In this scenario, downstream and upstream data are transmitted over a single wavelength using a single optical source located at the central office. FSK modulation has to be carried out at this point, since it is accomplished by direct modulation of the laser. Therefore downstream data is FSK-modulated while upstream data can be IM-modulated at the terminal unit. In this case only FSK to IM interference has to be taken into account, since in the downstream direction modulation formats do not coexist. Therefore, for this particular scenario there is no tradeoff in the choice of the IM extinction ratio, which should be as high as possible.

As Figure 1(a) shows, even for values of RIM modulation depth as high as 15%, which is associated to FSK frequency deviation of 1.3 GHz for the laser source considered in the experiments, SIR can be kept within reasonable values by increasing upstream ER.

4.3 Communications in transportation systems

Optical networks found in transportation systems are gradually demanding more bandwidth in order to accommodate an increasing range of services including infotainment and sensors for assisted advanced driving. Physical infrastructure of such networks must meet current and future requirements which tend to higher data rates (Mb/s to Gb/s) and lower latencies. In this context, Graded-Index Plastic Optical Fiber (GI-POF) and visible light VCSELs are foreseen as promising candidates; WDM transmission has also been proposed for POF [6]. The application of the proposed combination of modulation formats could also be implemented over POF, though for relatively low data rates thermal chirp may play a role and introduce additional transmission impairments.

5. CONCLUSIONS

We have analytically evaluated the crosstalk between data streams under an orthogonal modulation scheme based on IM/FSK formats. A tradeoff problem in the choice of the IM extinction ratio has been found, which can be solved by analyzing transmission performance of both data streams in order to find the value that meets system requirements. Optimum ER values depend on the particular application in terms of data rates involved and optical source characteristics. This modulation scheme has been successfully applied for labeling and for remote-seeded PON, while application to future automotive optical networks should take into account POF transmission issues and the arise of thermal chirp.

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