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Analysis of Optical Crosstalk in Subcarrier Multiplexed WDM Networks

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Abstract : In this study, we investigate the effects that optical crosstalk has on radio-over-fiber (ROF) wavelength division multiplexing (WDM) networks that make use of quadrature amplitude modulation (QAM) subcarrier modulation. Both the bit error rate (BER) and the power penalty are taken into consideration as we analyze the impact of optical crosstalk. OptiSystem, which is simulation software for optical communication, is used in order to check and see if the results are accurate. According to our findings, the presence of crosstalk that is brought on by shortcomings in the components might bring about a decline in the performance of the network. This research sheds light on the significance of reducing optical crosstalk in R-O-F WDM networks, in particular those that make use of QAM subcarrier modulation.

Key Words: Radio over Fiber (ROF), Optical crosstalk, Quadrature Amplitude Modulation (QAM), Wavelength division multiplexing (WDM), optical power penalty, Bit Error Rate.

Introduction

Sub carrier multiplexed (SCM) signals that utilize quadrature amplitude modulation (QAM) are required for wireless broadband access solutions such as Wi-Fi, WiMAX, and Universal Mobile Telecommunications System (UMTS). Radio over fiber (RoF) technology enables the use of passive antennas as base stations, which can then be connected to a central station via optical fiber. This helps to reduce the level of complexity and expense associated with radio-based access networks. This technology is particularly appealing for the implementation of Pico-cell infrastructures, as a solution for optical backhaul in wireless networks, and for the enhancement of digital services in cable television networks – (Yang *et al.*, 2016; Li *et al.*, 2017; Lim and Nirmalathas 2021)

The inherent nonlinear channel characteristics of RoF links, which differ from those of traditional air transmissions, present additional issues for the development of prospective internet access infrastructure (Louchet *et al.* 2008; Breyne *et al.* 2017; Lim *et al.*, 2019). RoF links are not the same as regular air transmissions. As depicted in Figure 1, a hybrid network known as a fiber-radio network transmits wireless data across an optical network from a central Office (CO) to remote base stations (BSs) (Yu *et al. 2023;* Zhu *et al.*, 2023). This type of network is known as a fiber-radio network. The CO serves as the interface between the various external networks that can be a Metropolitan Area Network (MAN) or Local Area Network (LAN), and a wireless network that consists of several BSs and offer wireless coverage to Mobile Units (MUs). The formation of a radio network is accomplished by having each BS cover a distinct radio cell . A fiber-radio network, as opposed to more conventional fiber-to-the-home (FTTH) access networks, transmits data at a wireless frequency rather than at baseband (Mähönen et al., 2001; Bhattacharjee et al., 2022). This is in contrast to FTTH networks. Relatively recently, the WDM networks have been used to support a large number of BSs by throgh a fiber-radio feeder network (Pincemin 2021; Deng et al., 2022). WDM networks, on the other hand, call for wavelength-selective optical components, which can result in the introduction of defects and consequently optical crosstalk—(Elsayed and Yousif, 2020). The performance of the network is not badly hindered by out-of-band crosstalk, which is generated by residual signals that optical components are unable to eliminate completely. On the other hand, in-band crosstalk happens when the signal being interfered with has the same wavelength as the signal being sought after, which results in phase-induced interferometer noise (PIIN) (Legg *et al.*, 1996).

Because it is at the same wavelength as the signal and cannot be filtered out, this type of crosstalk is far more destructive to the signal than the other types (Guan and Wang, 2008).

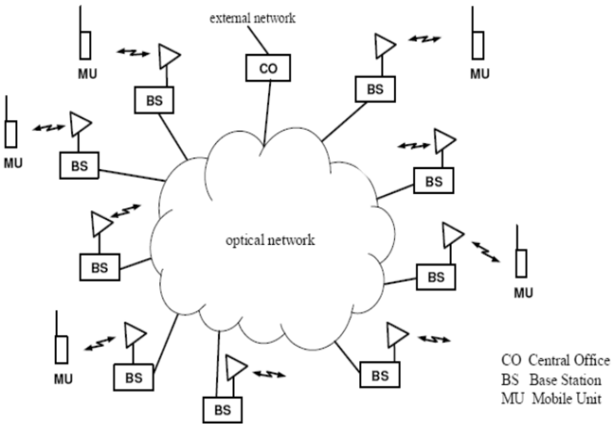

Fig. 1 Fibre-radio network comprising optical fiber and wireless networks.

Model of optical cross talk in 8- QAM subcarrier netwoks

For an externally modulated optical link with a modulated sub carrier at frequency RF driving an external Mach-Zehnder RF modulator, a straightforward model of in-band crosstalk is created taking into consideration the presence of a signal wavelength and one crosstalk wavelength. One way to express the electric field that is associated with optical signals of the same wavelength as those that are sought and those that cause crosstalk is as (Castleford et al., 2001):

$$E_1(t) = |E1|\cos(\omega t + \theta_1(t))\left[1 + m_1\alpha(t)\cos(\omega_{RF}(t) + \phi_1(t))\right]/2$$

$$E_2(t) = \sqrt{x}|E1|\cos(\omega t + \theta_2(t))\left[1 + m_2\beta(t)\cos(\omega_{RF}(t) + \phi_2(t))\right]/2$$

where E_1 and E_2 repersent the electric fields of the optical signals, ω is the optical frequency, m_1 and m_2 are modulation indices, α(t) and β(t) repersent the signal and crosstalk data respectively, x is the optical crosstalk power ratio, θ_1(t)and θ_2(t) are the optical phase and φ_1(t), φ_2(t) are the electrical phases. The optical crosstalk ratio is determiend by the ratio of crosstalk optical power to the optical signal power. The signal waveform $_{Idown}$ of the down converted baseband data channel can then be expressed as:

$$I_{down} = I(\omega_{RF})\cos(\omega_{RF}(t) + \phi_1(t)) \propto$$
$$m_1\alpha\left[1 + \sqrt{x}\cos(\theta_1 - \theta_2)\right] + m_2\beta\sqrt{x}\cos(\phi_1 - \phi_2)\left[\sqrt{x} + \cos(\theta_1 - \theta_2)\right]$$
$$= m_1\alpha\left[1 + \sqrt{x}\cos(\Delta\theta)\right] + m_2\beta\sqrt{x}\cos(\Delta\phi)\left[\sqrt{x} + \cos(\Delta\theta)\right]$$

Where I(ω_{RF}) denotes the amplitude of the RF carrier , $\Delta\varphi=\varphi_1(t)-\varphi_2(t)$ represents the signal channel and crosstalk signal RF phase difference, and $\Delta\theta = \theta_1 - \theta_2$ represents the the optical phase difference between two optical carriers. For Gaussian thermal receiver noise, bit-error rates (BERs) can be calculated using the complementary error function (Feldman et al. 1995),

$$BER = 1/2\, erfc\ (Q/\sqrt{2})$$

In the Eq. 6, Q was calculate by (I/σ), where I is the photocurrent and σ is the standard deviation of Gaussian PDF of thermal noise limited receiver. In light of the findings of the prior analysis, the expression for the signal that has been down converted in a case of out-of-band crosstalk is

$$I_{down} \propto m_1\alpha(t) + x m_2\beta(t)\cos(\Delta\phi)$$

This equation demonstrates that the sole factor that influences out-of-band crosstalk is the RF phase difference; as a result, it is easy to achieve a reduction in the amount of crosstalk that occurs when Δϕ= 90°. Furthermore, the data on the signal and the data on the crosstalk are both recovered independently, and there are no mixing terms between the signal and the crosstalk at the appropriate RF frequency. This is because the frequency separation of the optical carriers would generally be a significant amount higher than the frequency of RF modulation in the wireless network. Quantum amplitude modulation (QAM) is a type of digital modulation that stores digital information in the amplitude as well as the phase of the transmitted carrier. Figure 2 depicts a typical 8-QAM constellation, which reveals the presence of 8 possible signal points with the additional cross talk components X_x and X_y, where X_x and X_y correspond to the I and Q amplitudes in-phase with the crosstalk carrier

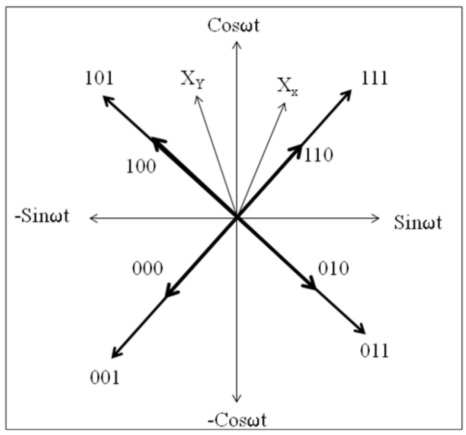

Fig. 2 Signal constellation showing 8-QAM signal and offset crosstalk signal

With the help of Figure 2, we were able to derive the following equations for the in-phase (I) component.

$$I_{n1} = -0.541X_x Cos(\Delta\varphi) - 0.541X_y Sin(\Delta\phi)$$
$$I_{n2} = -1.307X_x Cos(\Delta\varphi) - 1.307X_y Sin(\Delta\phi)$$
$$I_{n3} = 0.541X_x Cos(\Delta\varphi) + 0.541X_y Sin(\Delta\phi)$$
$$I_{n4} = 1.307X_x Cos(\Delta\varphi) + 1.307X_y Sin(\Delta\phi)$$
$$I_{n5} = -0.541X_x Cos(\Delta\varphi) + 0.541X_y Sin(\Delta\phi)$$
$$I_{n6} = -1.307X_x Cos(\Delta\varphi) + 1.307X_y Sin(\Delta\phi)$$
$$I_{n7} = 0.541X_x Cos(\Delta\varphi) - 0.541X_y Sin(\Delta\phi)$$
$$I_{n8} = 1.307X_x Cos(\Delta\varphi) - 1.307X_y Sin(\Delta\phi)$$

Similarly for Quadrature component, equations will be:

$$Q_{n1} = -0.541X_x Sin(\Delta\varphi) - 0.541X_y Cos(\Delta\phi)$$
$$Q_{n2} = -1.307X_x Sin(\Delta\varphi) - 1.307X_y Cos(\Delta\phi)$$
$$Q_{n3} = 0.541X_x Sin(\Delta\varphi) + 0.541X_y Cos(\Delta\phi)$$
$$Q_{n4} = 1.307X_x Sin(\Delta\varphi) + 1.307X_y Cos(\Delta\phi)$$
$$Q_{n5} = -0.541X_x Sin(\Delta\varphi) + 0.541X_y Cos(\Delta\phi)$$
$$Q_{n6} = -1.307X_x Sin(\Delta\varphi) + 1.307X_y Cos(\Delta\phi)$$
$$Q_{n7} = 0.541X_x Sin(\Delta\varphi) - 0.541X_y Cos(\Delta\phi)$$
$$Q_{n8} = 1.307X_x Sin(\Delta\varphi) - 1.307X_y Cos(\Delta\phi)$$

Expressions for X_X and X_Y are given by:

$$X_x = \beta_x \left[x + \sqrt{x} Cos(\Delta\theta)\right]$$
$$X_y = \beta_y \left[x + \sqrt{x} Cos(\Delta\theta)\right]$$

Where $_X$ and $_Y$ are crosstalk in I and Q data amplitudes respectively, taking values of ±1, and Δθ is the optical phase difference between signal and crosstalk optical carriers. Similarly, I and Q components in-phase with the signal carrier are given by:

$$S_x = \alpha_x \left[1 + \sqrt{x} Cos(\Delta\theta)\right]$$
$$S_y = \alpha_y \left[1 + \sqrt{x} Cos(\Delta\theta)\right]$$

The resulting received in-phase component, I_{TOTAL} is given by

$$I_{TOTAL} = S_x + I_n$$

And the quadrature component, Q_{TOTAL} is given by

$$Q_{TOTAL} = S_y + I_n$$

Both I and Q expressions depend on the signal data and crosstalk data so, there are sixteen possible bit combinations in each case. Inspection of the equations (6 to 11) leads to the following identical bit combinations.

$$I_{0000} = -I_{0111} = Q_{0010} = -Q_{0101}$$
$$I_{0001} = -I_{0110} = Q_{0000} = -Q_{0111}$$
$$I_{0010} = -I_{0101} = Q_{0011} = -Q_{0100}$$
$$I_{0011} = -I_{0100} = Q_{0001} = -Q_{0110}$$
$$I_{1000} = -I_{1111} = Q_{1010} = -Q_{1101}$$
$$I_{1001} = -I_{1110} = Q_{1000} = -Q_{1111}$$
$$I_{1010} = -I_{1101} = Q_{1011} = -Q_{1100}$$
$$I_{1011} = -I_{1100} = Q_{1001} = -Q_{1110}$$

Out-of-band expressions for 8-QAM are:

$$I_{TOTAL} = \alpha_x + 0.541\beta_x Cos(\Delta\phi) - 0.541\beta_y Sin(\Delta\phi)$$
$$Q_{TOTAL} = \alpha_y + 0.541\beta_x Sin(\Delta\phi) + 1.307\beta_y Cos(\Delta\phi)$$

Results and discussions

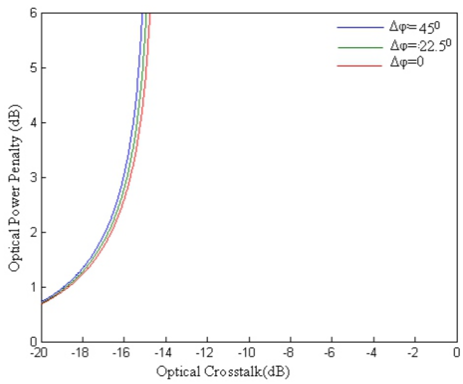

Fig. 3 Optical power penalties for in-band crosstalk for 8-QAM modulation

The optical power penalty that was calculated for different amounts of cross talk with variable RF phase differences is depicted in Figures 3 and 4, respectively, for in-band and out-of-band crosstalk, respectively. In the case of in-band crosstalk, the optical power penalty is significantly higher than it is in the case of out-of-band crosstalk for the same amount of crosstalk, and it rises precipitously as the amount of crosstalk grows. On the other hand, the reliance of optical power penalty on RF phase difference is significantly higher in the case of out-of-band crosstalk.

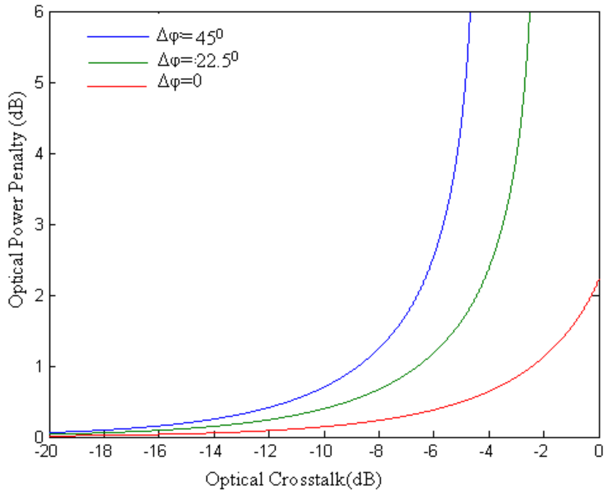

Fig. 4 Optical power penalties for out-of-band crosstalk for 8- QAM modulation

The dependency of bit error rate (BER) on RF phase difference is depicted in Figure 5 (a) and (b), respectively, for in-band crosstalk levels of –30 dB and –10 dB. This demonstrates that the BER increased from 1.2 x 10^{-8} to 1.0 x 10^{-2} when the cross talk level was adjusted from –30 dB to –10 dB. This indicates that an increase in in-band crosstalk brings about a substantial decline in system performance.

A commercial optical link simulation software package, Optiwave, was used to conduction the virtual experiment. The Optiwave environment provides access to a wide variety of optical and electrical components that can be put to use in the process of designing and simulating an optical communication system of one's choosing. The results of the simulation of the optical power penalties for in-band crosstalk and out-of-band crosstalk, respectively, for the 8-QAM subcarrier modulation scheme are shown in Figures 6(a) and 6(b).

Table 1. COMPARISION OF RESULTS

Type Of cross-talk	Evaluated results	Simulation results
In-band	-19 dB	-19 dB
Out-of-band	-9.5 dB	-9.0 dB

The results of theoretical evaluations are compared with the outcomes of simulations in Table 1. We have displayed in this table the optical crosstalk level for the 8-QAM system at which a 1 dB optical power penalty will occur for both in-band and out-of-band crosstalk at the same time. As a result of looking at this table, we have reached the conclusion that in-band crosstalk is more important when it comes to subcarrier modulation. This table demonstrates, in addition, that our theoretical findings are in reasonable agreement with the findings of the simulation..

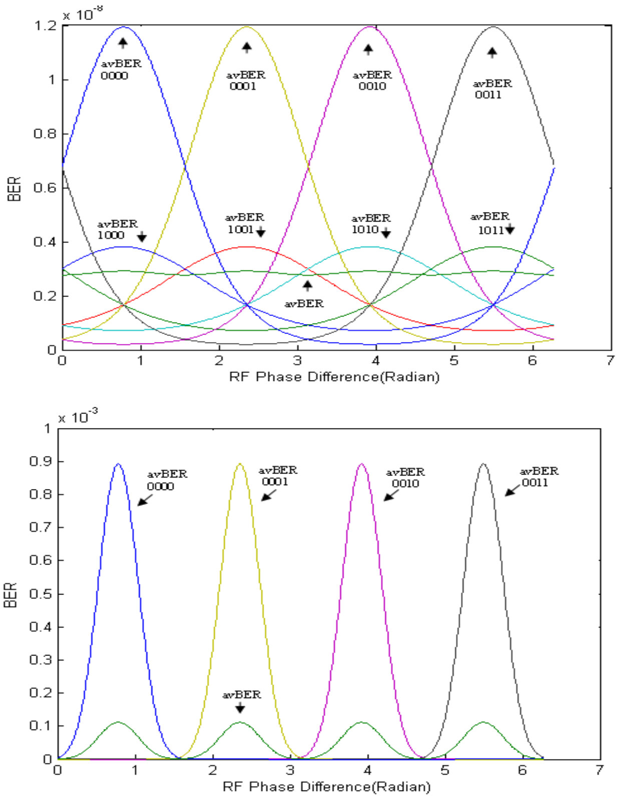

Fig. 5 BER versus RF phase difference (a) for – 30 dB crosstalk and (b) for– 10 dB in-band crosstalk

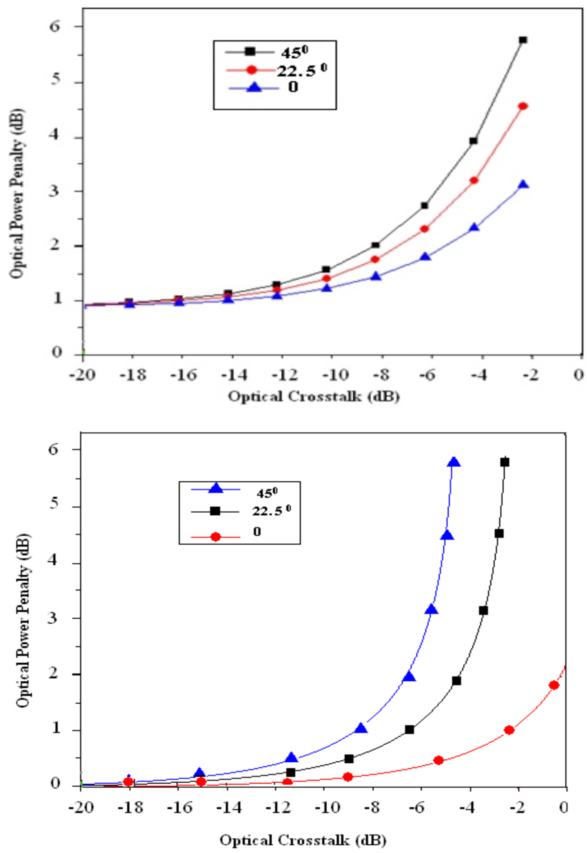

Fig.6 optical power penalties (a) for in-band Crosstalk (b) for out-of-band cross talk (simulation)

Conclusion

As the outcome of our research, we have been able to design a straightforward model for measuring in-band and out-of-band crosstalk in 8-QAM subcarrier WDM networks. This model takes into consideration a signal wavelength in addition to a single crosstalk wavelength. We have determined the effect that crosstalk has on both the optical power penalty and the BER, and we have described how both metrics are dependent on the level of optical crosstalk as well as the RF phase difference. The validity of our model has been established by comparison with simulations run on OptiSystem. The theoretical results and the simulation results have been shown to be in good agreement with one another. The insights that we acquired from our analysis can help in the design and optimization of WDM networks for greater performance when there is crosstalk present in the environment.

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