Impact of Optical Crosstalk in Fibre-Radio Systems Incorporating WDM

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ABSTRACT: We investigate analytically and experimentally optical crosstalk effects in fibre-radio systems incorporating wavelength-division multiplexing. Both in-band and out-of-band crosstalk are considered and the effect of the RF phase difference between the desired and crosstalk channels investigated. It is found that in-band incoherent crosstalk-induced power penalties are less severe than in conventional baseband transmission.

1 Introduction

The fibre-radio concept allows the distribution of broadband wireless signals between a large number of antenna base stations (BSs) and central office (CO) over optical fibre [1]. Typically in these networks radio signals are transported over the optical fibre as either intermediate frequency (IF) or radio frequency (RF). The application of optical networking concepts to fibre-radio systems has recently been proposed [2-5]. The use of wavelength division multiplexing (WDM) can simplify the network architecture using wavelengths to feed different antenna BSs, can support multiple interactive services on one fibre, and can greatly simplify network upgrades.

In any optical network incorporating WDM, optical crosstalk occurs due to imperfect optical components and leads to unwanted wavelengths interfering with the desired optical channel. The impact of optical crosstalk in the context of baseband optical transmission has been actively investigated [6-7]. These studies have shown that optical crosstalk can lead to severe system performance impairments such as power penalties and bit-error-rate (BER) floors. Previous investigations of fibre-radio systems incorporating WDM have considered possible network architectures and experimental implementations [2-5]. In addition, Griffin *et al.* [4] have examined the effect of crosstalk resulting from the modulator nonlinearity in a fibre-radio system operating at millimetre-wave frequencies. In this paper we present an analytical formulation for optical crosstalk effects in fibre-radio systems which can account for all potential sources of crosstalk. Both in-band and out-of-band crosstalk are considered and the model is confirmed by experiment.

Fig. 1 Typical fibre-radio WDM ring network

2 Fibre-Radio Architecture

Fig. 1 shows an architecture for a typical fibre-radio system based on a WDM ring network. A CO distributes a number of wavelengths each carrying multiple modulated RF subcarriers. The ring topology allows the allocation of a single wavelength to a particular BS and the wavelength routing is enabled via optical add-drop multiplexers (OADMs). Upstream signal transmission is achieved by modulating upstream radio signals onto an optical carrier at the same BS wavelength, and adding it back into the ring via the OADM. As can be seen from the ring topology, two types of crosstalk can arise, namely in-band (homodyne) crosstalk and out-of-band (heterodyne) crosstalk. In-band crosstalk is at the same wavelength as the signal and occurs either when the 'add' wavelength or a reflected/delayed version of the dropped wavelength is present at the dropped channel. Meanwhile out-of-band crosstalk is by definition at a different wavelength and occurs when part of the 'through' wavelengths appear at the 'dropped' channel.

In the case of in-band crosstalk, the crosstalk can be both coherent or incoherent. Coherent crosstalk occurs when the crosstalk signal is a delayed version of the dropped channel, due to reflections or path delays in optical components, and the path length difference is less than the coherence length of the optical signal. If the path length difference is greater than the coherence length or the crosstalk signal arises from leakage of the 'add' wavelength (where the

optical source providing the ‘add’ wavelength is different to that supplying the ‘drop’ wavelength), then the in-band crosstalk is also incoherent. Meanwhile, out-of-band crosstalk resulting from unwanted WDM channels arising from different optical sources being present at the receiver, is inherently incoherent. In order to investigate crosstalk effects in fibre-radio systems which transport RF carriers, the electrical phase of the modulated RF signal must also be taken into account in addition to the optical phase of the desired channel and crosstalk signal.

3 In-band Crosstalk

In order to investigate the effect of optical crosstalk in fibre-radio systems, a simple analytical model was developed for both in-band and out-of-band crosstalk. The model includes the simple case of one wavelength channel and one interfering crosstalk signal. For an intensity modulation direct-detection system where a modulated subcarrier frequency ω_{RF} is applied to an external modulator, the desired and in-band crosstalk optical signals can be represented as:

$$\begin{aligned} E_1(t) &= E_1 \cos(\omega t + \theta_1) [1 + m_1 \cos(\omega_{RF} t + \phi_1)] \\ E_2(t) &= \sqrt{x} E_1 \cos(\omega t + \theta_2) [1 + m_2 \cos(\omega_{RF} t + \phi_2)] \end{aligned} \quad (1)$$

where E_1 , E_2 are the electric fields of the optical signals, ω is the optical frequency, m_1 and m_2 are modulation indices, x is the optical crosstalk power ratio, θ_1 and θ_2 represent the optical phase, and ϕ_1 , ϕ_2 are the electrical phases. If the in-band crosstalk is also coherent, then a fixed relationship exists between the two optical phase angles and the two electrical phase angles.

The effect of the optical crosstalk signal is to produce an additional unwanted RF signal component at ω_{RF} upon detection. The detected photocurrent I is proportional to the square of the electric field via:

$$I \propto (E^2) = (E_1 + E_2)^2 \quad (2)$$

The presence of two different signals at the same optical wavelength results in the following frequency components at ω_{RF} :

$$\begin{aligned} I(\omega_{RF}) &\propto m_1 \cos(\omega_{RF} t + \phi_1) \\ &\quad + x m_2 \cos(\omega_{RF} t + \phi_2) + \sqrt{x} \cos(\theta_1 - \theta_2) \\ &\quad \times [m_1 \cos(\omega_{RF} t + \phi_1) + m_2 \cos(\omega_{RF} t + \phi_2)] \end{aligned} \quad (3)$$

The first two terms in Eqn. 3 represent the recovered ω_{RF} frequencies from the optical channel and the crosstalk signals themselves, respectively, while the last two terms are due to intermixing of the two optical carriers with the modulation sidebands of the other signal.

If the RF subcarrier at ω_{RF} is modulated with data in binary phase shift key (BPSK) format, a phase-locked loop (PLL) must be employed to recover the data. This PLL must be locked to the phase of the wanted channel, i.e. ϕ_1 . The signal waveform of the downconverted data channel (using a PLL) can then be represented by:

$$\begin{aligned} I_{down} &= I(\omega_{RF}) \cos(\omega_{RF} t + \phi_1) \\ &\propto m_1 (1 + \sqrt{x} \cos(\theta_1 - \theta_2)) \\ &\quad + m_2 \sqrt{x} \cos(\phi_1 - \phi_2) [\sqrt{x} + \cos(\theta_1 - \theta_2)] \\ &= m_1 [1 + \sqrt{x} \cos(\Delta\theta)] \\ &\quad + m_2 \sqrt{x} \cos(\Delta\phi) [\sqrt{x} + \cos(\Delta\theta)] \end{aligned} \quad (4)$$

where $\Delta\phi = \phi_1 - \phi_2$ is the RF phase difference between the desired channel and crosstalk signal, and $\Delta\theta = \theta_1 - \theta_2$ is the optical phase difference between the two optical carriers. Eqn. 4 shows that due to the multiplication effect of the PLL, the mixing products arising from the crosstalk signal itself and intermixing terms due to the signal carrier and crosstalk sidebands beating are multiplied by $\cos(\Delta\phi)$. This RF phase difference is clearly crucial since orthogonal RF carriers are rejected by the PLL.

We assume that $m_1 = m_2$ and the modulation format is BPSK. Assuming only Gaussian thermal receiver noise allows use of the complementary error function to calculate the BER [8]:

$$BER = \text{Erfc}(Q / \sqrt{2}\sigma) \quad (5)$$

where $Q = (I / \sigma)$ (decision threshold = 0) and σ is the standard deviation of the Gaussian thermal noise. When both the signal and crosstalk are present, I will vary depending on the four equiprobable logic bit combinations: 00, 01, 10 and 11. The average BER for a given crosstalk power ratio (x), optical phase difference ($\Delta\theta$) and RF phase difference ($\Delta\phi$) as well as signal power can then be calculated using Eqns. 4 and 5. In the case of coherent crosstalk, $\Delta\theta$ will be constant. Meanwhile incoherent crosstalk will lead to a stochastically varying $\Delta\theta$ (uniformly distributed between 0 and 2π) which therefore requires the averaging of BER over $\Delta\theta$. By varying the signal power and the crosstalk ratio, a set of BER curves can be obtained and optical power penalties for a BER = 10^{-9} calculated.

Fig. 2 shows the in-band incoherent crosstalk predicted using the analytical model, as a function of crosstalk level for $\Delta\phi = 0, \pi/4$, and $\pi/2$. In Fig. 2, the crosstalk ratio varies from -20 dB to 0 dB. In a single OADM, the ‘add’-‘drop’ in-band crosstalk is in the order of -30 dB or better, while rejection of out-of-band WDM channels is typically -20 to -30 dB. However the crosstalk levels can rapidly increase in a cascaded system of OADMs. For comparison, Fig. 2 also plots the predicted power penalty for baseband data transmission. These results show that the power penalties arising from in-band crosstalk can vary depending on the RF phase difference between the crosstalk and desired signals. For example, at a crosstalk level of -12 dB, the power penalty is reduced by ~1.5 dB when $\Delta\phi$ is changed from 0 to $\pi/2$. This is to be expected as the full crosstalk signal amplitude is recovered by the PLL when $\Delta\phi = 0$. The difference in power penalties also increases with increasing x (e.g. ~4 dB at a crosstalk level of -4 dB). Fig. 2 also shows that

Fig. 2 Predicted optical power penalty versus optical crosstalk ratio due to in-band incoherent crosstalk

the crosstalk-induced optical power penalty is significantly worse in the case of baseband data transmission. This is due to the effect of the optical and electrical phase differences as well as the bipolar nature of the BPSK modulation format.

In order to confirm the analytical model, a commercially available optical link design simulation tool was used to analyse the effect of crosstalk. Fig. 2 also shows these numerical simulation results of power penalty indicating that very close agreement with the analytical model was obtained. It should be noted that the analytical model for in-band crosstalk assumes polarisation alignment of the desired channel and the crosstalk signal thereby giving predictions of optical power penalties which represents 'worst-case' scenarios in the network [9].

4 Out-of-band Crosstalk

4.1 Analytical Model

We now consider crosstalk arising from a signal that is at a different wavelength from the desired channel which can be represented as (following the previous analysis):

$$\begin{aligned} E_1(t) &= E_1 \cos(\omega_1 t + \theta_1) [1 + m_1 \cos(\omega_{RF} t + \phi_1)] \\ E_2(t) &= \sqrt{x} E_2 \cos(\omega_2 t + \theta_2) [1 + m_2 \cos(\omega_{RF} t + \phi_2)] \end{aligned} \quad (6)$$

where ω_1 and ω_2 represent the optical frequencies of the desired channel and the crosstalk signal, respectively. Ignoring all of the possible mixing terms at frequencies other than ω_{RF} , we get:

$$\begin{aligned} I(\omega_{RF}) &= I(\omega_{1RF}) + I(\omega_{2RF}) \\ &\propto m_1 \cos(\omega_{RF} t + \phi_1) \\ &\quad + \sqrt{x} m_2 \cos(\omega_{RF} t + \phi_2) \end{aligned} \quad (7)$$

As before, recovery of BPSK modulation using a PLL will result in the following downconverted signal:

$$\begin{aligned} I_{down} &= I(\omega_{RF}) \cos(\omega_{RF} t + \phi_1) \\ &= m_1 + \sqrt{x} m_2 \cos(\phi_1 - \phi_2) \\ &= m_1 + \sqrt{x} m_2 \cos(\Delta\phi) \end{aligned} \quad (8)$$

Comparing Eqn. 8 to Eqn. 4 shows that out-of-band crosstalk is only influenced by the RF phase difference, and therefore a potential reduction of crosstalk is possible when $\Delta\phi = \pi/2$.

Fig. 3 shows the predictions of the analytical model for out-of-band crosstalk for $\Delta\phi = 0, \pi/4$ and $\pi/2$, as a function of optical crosstalk ratio. Also shown in the figure is the predicted power penalty for baseband transmission. As for the case of in-band crosstalk, the optical power penalties for out-of-band optical crosstalk vary with $\Delta\phi$, with the largest power penalty occurring for $\Delta\phi = 0$. The actual power penalty for a particular crosstalk ratio however, is less for out-of-band crosstalk than for the in-band case. For example in Fig. 3, at -12 dB of crosstalk, the power penalty for all values of $\Delta\phi$ is less than 0.5 dB. In addition, the variation of power penalty with $\Delta\phi$ is reduced to less than 0.25 dB at the same crosstalk level. Fig. 3 shows that for an RF phase difference of $\Delta\phi = \pi/2$, when the crosstalk signal is at the same optical power as the desired channel (0 dB of optical crosstalk), the optical power penalty is 3 dB. This is as expected since the $\pi/2$ phase shift leads to a cancellation of the crosstalk contribution.

In contrast to the case for in-band crosstalk where the optical power penalty for baseband data transmission was significantly higher than for RF subcarrier transmission (at all crosstalk ratios), Fig. 3 shows that out-of-band crosstalk induced power penalties for baseband data transmission are very similar to those for RF subcarrier transmission.

Fig. 3 Theoretical and experimental optical power penalties due to out-of-band incoherent crosstalk

4.2 Experiment

An experiment was carried out in order to confirm the theoretical predictions of out-of-band crosstalk. Fig. 4 shows the experimental setup. The desired channel and crosstalk signal are implemented by two separate optical paths, each comprising a distributed feedback laser ($\lambda_1 = 1549.4$ nm, $\lambda_2 = 1550$ nm) and an electro-optic modulator (EOM). Separate data channels at 155 Mb/s modulate an RF signal at 2 GHz in BPSK modulation format. An RF phase shifter was used to control the RF phase difference between the desired channel and crosstalk signal. The two signals are coupled together and amplified using

an erbium-doped fibre amplifier (EDFA) in order to compensate for losses in the optical link. An optical bandpass filter (BPF) with a bandwidth of 2 nm was included after the EDFA in order to filter out excess ASE. At the receiver, the optical signals are detected using a p-i-n photodetector (PD) and the same 2 GHz signal is used to downconvert the detected modulated RF signals and recover the data. A bit-error-rate testset (BERT) measures the BER of the recovered 155 Mb/s data as a function of optical crosstalk ratio (varied via the optical attenuator in the optical path of λ_2). By measuring a BER curve at a particular crosstalk ratio and carrying out a back-to-back system measurement, the crosstalk-induced optical power penalty could be determined. Fig. 3 shows the measured optical power penalty at a BER of 10^{-9} as a function of optical crosstalk ratio, for $\Delta\phi = 0, \pi/4$ and $\pi/2$, plotted alongside the theoretical predictions for out-of-band crosstalk. The measurements show very good agreement with theory, with a small discrepancy between the two sets of results appearing at higher crosstalk levels (> -4 dB). This is most likely due to experimental error and possible optical and electrical nonlinearities in the system.

Fig. 4 Experimental setup for measurement of out-of-band crosstalk

5 Discussion and Conclusions

The predictions of in-band and out-of-band crosstalk induced power penalties clearly show that for fibre-radio systems which employ RF over fibre signal transmission, the effect of in-band crosstalk is much more significant. For example when $\Delta\phi = \pi/4$, at a crosstalk ratio of -8 dB, in-band incoherent crosstalk causes an optical power penalty of 4 dB, while that due to out-of-band incoherent crosstalk is only 1 dB. When comparing the in-band crosstalk-induced penalties for RF and baseband data transmission, a 1 dB penalty occurs at -17 dB of crosstalk for BPSK data transmission, however the same penalty arises at only -23 dB of crosstalk in baseband transmission. This shows the greater tolerance to the effect of optical crosstalk in RF over fibre

transmission employing BPSK modulation. In the case of out-of-band crosstalk, the crosstalk-induced power penalties in both the baseband and RF over fibre transmission schemes (for $\Delta\phi = 0$) are identical (-10 dB of crosstalk ratio giving a 1 dB optical power penalty) with the penalty reducing as $\Delta\phi$ goes to $\pi/2$. While the results presented in Figs. 2 and 3 apply to a single interfering crosstalk signal, the analytical model can be extended to accommodate an increased number of crosstalk signals.

We have presented a simple analytical model which can predict optical power penalties due to in-band and out-of-band optical crosstalk in fibre-radio systems employing WDM. The model considers the case of a single crosstalk interfering signal, a BPSK modulation format for RF over fibre transmission and also accounts for the RF phase difference between the desired channel and crosstalk signal. The model has been validated by measurement of out-of-band crosstalk, and future experimental work will investigate in-band crosstalk effects.

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