In-band Optical Crosstalk in Fiber-Radio WDM Networks

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Abstract — **We present the first experimental investigation of the impact of in-band optical crosstalk in fiber-radio networks incorporating wavelength division multiplexing. We show that crosstalk-induced power penalties are reduced when the crosstalk signal carries a different wireless frequency band, however penalties are still observed even for perfect RF filtering of the crosstalk signal.**

I. INTRODUCTION

Optical fiber feeder networks are being considered for the distribution of wireless signals from a central office (CO) to remote antenna base-stations (BSs). Wavelength-division multiplexed (WDM) network concepts are also being applied to these fiber-wireless access networks to enable simple service upgrades and additional BS deployment [1].

While the impact of optical crosstalk has been extensively investigated in WDM optical networks employing baseband data transmission [2], little work has been carried out for the case of analog modulation at intermediate or radio frequencies (IF or RF). For example, Moura et al. [3] considered the impact of optical crosstalk due to reflections for ASK optical carrier-suppressed modulated data and showed that penalties were reduced compared to baseband transmission. In addition, we have previously presented a simple theoretical model that allows power penalties due to optical crosstalk in fiber-radio WDM systems to be calculated. In [4], we considered the case of binary phase-shift keying (BPSK) modulation and also presented experimental results for the case of out-of-band optical crosstalk.

In this paper, we present the first experimental investigation of the impact of in-band optical crosstalk in fiber-radio WDM systems. We consider two particular situations that may arise: where the optical signal and crosstalk channels transport data at similar and different wireless frequencies. We show that crosstalk-induced power penalties are significantly lower when the in-band crosstalk channel is carrying a different set of wireless frequencies, however power penalties are still observed even for perfect RF filtering of the crosstalk signals.

II. WDM FIBER-RADIO ACCESS NETWORKS

A. Typical Network Topologies

Fig. 1 shows two possible WDM fiber-radio network topologies: the ring and star architectures. In the ring network shown in Fig. 1(a), a single wavelength feeds a particular BS (or group of BSs), and is dropped from the ring in the downstream direction by an optical add-drop multiplexer (OADM). In a ring network, efficient spectral use dictates that identical downstream and upstream wavelengths are used, also minimizing optical component requirements and simplifying network management. The same OADM therefore allows the wavelength to be re-used and added back to the ring for upstream transmission back to the CO. A bi-directional link is depicted in Fig. 1(a) linking the ring to the CO, but is not necessarily required.

In the case of the star network (Fig. 1(b)), an arrayed-waveguide grating multiplexer (AWGM) is used to separate wavelengths in the downstream direction for routing to a particular BS and re-combine the upstream optical signals. In Fig. 1(b) all links are bi-directional and different up- and downstream wavelengths are used at each BS so as to minimize the impact of reflections. The free spectral range of the AWGM allows different wavelengths to be recombined in the upstream direction using the same device.

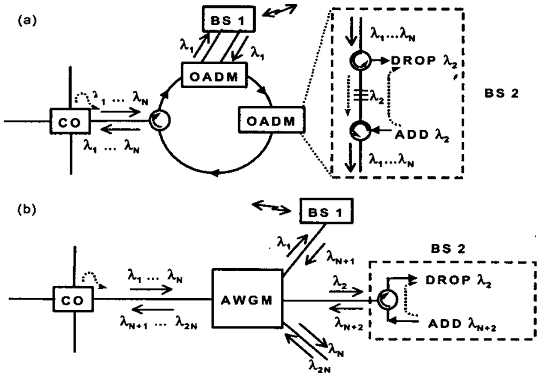

Fig. 1. Fiber-radio WDM network architectures.

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B. Out-of-band Crosstalk

In fiber-radio WDM networks two types of optical crosstalk can arise depending on whether the crosstalk channel is at the same wavelength as the signal. For example, a non-perfect fiber Bragg grating (FBG) or AWGM means that BS 1 not only receives the optical wavelength λ_1 it is assigned, but also other unwanted wavelengths $\lambda_2 \ldots \lambda_N$. The level of this so-called "out-of-band" crosstalk depends on the filtering characteristics of the optical components (e.g. –35 dB for a FBG or –25 dB for an AWGM) and results in power penalties that can be calculated using conventional electrical crosstalk analysis techniques [5].

Another possible source of out-of-band crosstalk can occur in the case of the star architecture as a result of reflections along the bi-directional links due to imperfect or faulty components (-40 to –10 dB). Note that Rayleigh backscatter will also occur along the fiber. In the fiber-radio network each wavelength will be modulated with multiple IF or RF wireless channel frequencies. If frequency re-use is implemented in the radio network where other wavelengths destined for non-adjacent radio cells carry the same radio frequency band, significant crosstalk may occur since it will not be possible to filter the unwanted radio signals at the same electrical frequency.

C. In-band Crosstalk

"In-band" optical crosstalk occurs due to an unwanted signal at the same wavelength as the desired signal and cannot be optically filtered. In the case of the ring architecture where the same wavelength is re-used by a single BS, some of the downstream (dropped) wavelength will leak through the FBG and cause in-band crosstalk at the CO, while some of the upstream (added) wavelength will again leak through the FBG and cause in-band crosstalk at the BS. In the case of the star fiber-radio architecture, in-band optical crosstalk can occur within the AWGM however this will be coherent, while in-band incoherent crosstalk from other sources may occur at the CO, coming from other stars of the network covered by the CO. Here again, the use of frequency re-use will lead to the desired and crosstalk channels carrying the same wireless frequency bands.

In contrast to out-of-band optical crosstalk, power penalties due to in-band crosstalk are different to those arising from electrical interference. This is due to the fact that the optical spectrum comprises modulation sidebands centered about the unmodulated optical carrier. The square-law response of a photodetector results in intermixing terms, some of which produce the required IF/RF electrical signal. For baseband modulation, the optical carrier itself is modulated and mixing terms produce the baseband electrical signal. This difference explains the observed difference in predicted power penalties, which are worse for the case of baseband modulation [3,4]. Even if the in-band optical crosstalk channel is carrying a different set of electrical frequencies which are filtered by the receiver, an optical power penalty will still result due to these mixing terms.

III. INBAND CROSSTALK WITH RADIO FREQUENCY RE-USE

A. Experiment

Fig. 2 shows the experimental set-up used for the measurement of optical power penalties at varying RF phase differences due to in-band optical crosstalk in a fiber-radio network with radio frequency re-use. A DFB laser at wavelength λ_1 provides both the desired optical signal and the inband crosstalk component. The two optical signals are each externally modulated by an RF carrier at 3.5 GHz carrying 155 Mb/s data in BPSK modulation format (two separate data generators provide the 155 Mb/s radio data). An electrical phase shifter is included in the crosstalk electrical path in order to investigate the effect of any RF phase difference between the signal and crosstalk wireless channels.

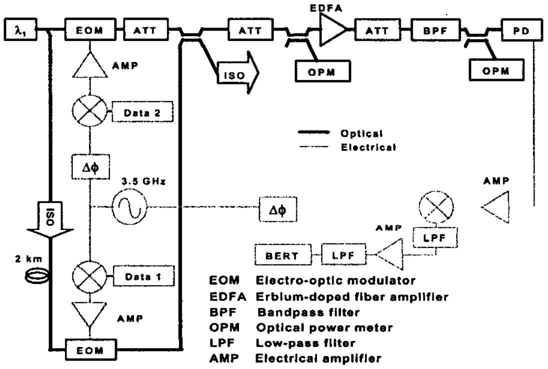

Fig. 2. Experimental set-up for measurement of in-band optical crosstalk.

An attenuator (ATT) in the optical path of the crosstalk optical signal is used to vary its amplitude in order to investigate power penalties due to varying levels of in-band crosstalk. A 2 km long spool of single-mode fiber ensures that the optical signals are rendered incoherent, which means that the optical phase differences between the desired and crosstalk signals are random and time-averaged over a bit-period. An optical isolator (ISO) also ensures that Rayleigh backscatter does not affect the laser or the other optical path. After the optical channel and crosstalk signals are modulated, they are combined and amplified before being detected using a photodiode (PD). The recovered RF carrier is then amplified and downconverted to recover the 155 Mb/s data. A bit-error-rate testset (BERT) is used to measure the BER curve at a particular optical crosstalk level, and the power penalty for a BER of 10^{-9} determined.

B. Theoretical and Experimental Results

Fig. 3 shows the measured optical power penalties due to in-band optical crosstalk in a fiber-radio network with radio frequency re-use (where the optical channel and crosstalk signals carry the same wireless frequency at 3.5 GHz). Also shown in Fig. 3 for comparison are the predicted power penalties using the theoretical model first presented in [4]. The power penalties were determined for the possible situation of an RF phase difference between the desired and crosstalk signals, with phase differences of 0°, 45° and 90° shown in Fig. 3. As expected, the largest power penalties are observed for no RF phase difference (where the RF carriers are aligned), whereas orthogonal carriers produce the lowest penalties.

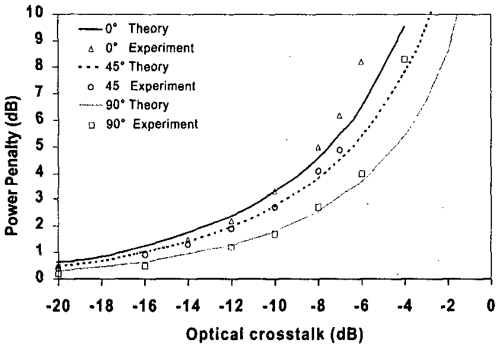

Fig. 3. Measured and predicted optical power penalties due to in-band optical crosstalk with radio frequency re-use.

Compared to the measured and predicted optical power penalties for out-of-band optical crosstalk (presented in [4]), the penalties are significantly worse for in-band crosstalk due to the extra beat terms (between the signal and crosstalk components) that arise which produce a signal at the desired RF frequency. Even for the case of an orthogonal electrical crosstalk carrier which is filtered out by the receiver, a significant power penalty is observed. This result has important implications for the design of fiber-radio WDM networks. Increasing levels of in-band optical crosstalk and an orthogonal RF crosstalk carrier result in an error floor being observed above a BER of 10^{-9} when the crosstalk level is 0 dB. In contrast, the same situation for out-of-band crosstalk produces an optical power penalty of only 3 dB. This is due to the presence of the in-band optical crosstalk carrier that can beat with the signal modulation sidebands, varying the electrical signal amplitude as a function of the crosstalk level and optical phase difference. The measured optical power penalties in Fig. 3 show good agreement with the predicted values for levels of in-band crosstalk up to – 6 dB.

IV. CROSSTALK DUE TO DIFFERENT RADIO FREQUENCIES

A. In-band Crosstalk

Section III investigated optical power penalties that can arise in a fiber-radio WDM network where radio frequency re-use is implemented and the optical channel and crosstalk signal carry the same radio frequency band. The situation where the channel and crosstalk signal carry different RF frequencies will also occur, since different wireless frequencies are used in the radio down- and uplinks. In a traditional electrical interference analysis, these wireless frequencies would be sufficiently separated so as to minimize electrical interference using appropriate channel spacing and electrical filters. Although this is also true in the optical domain for different wavelengths, this is not the case for in-band optical crosstalk. Even if different electrical frequencies are used, in-band optical crosstalk will result in a power penalty. The situation is in effect the same as that for in-band crosstalk with the same electrical frequency but with orthogonal RF carriers. Although electrical filters may fully remove the unwanted RF crosstalk signal when it is at a different electrical frequency, the presence of the optical crosstalk carrier means that the same "fading" effect occurs. As the electrical frequency separation is reduced and electrical filtering becomes less and less effective, one approaches the in-band optical crosstalk case for identical RF frequencies. A worst-case scenario would then occur for in-phase RF carriers while for different wireless frequencies, the instantaneous phase differences are time varying.

Fig. 4 shows the predicted optical power penalties due to in-band optical crosstalk for the case of perfect electrical filtering of different RF frequencies (best case) and the case of identical electrical frequencies and phase alignment (worst case). Also shown in Fig. 4 are the measured penalties when the desired and crosstalk wavelengths carry wireless frequencies separated by 300 MHz, 150 MHz, and 75 MHz. This was achieved by using a separate RF synthesizer for the crosstalk BPSK data and the receiver circuit comprised electrical filters of 150 MHz bandwidth that minimized the effect of neighboring frequencies. The measured results in Fig. 4 are bounded between the predicted best- and worst-case scenarios.

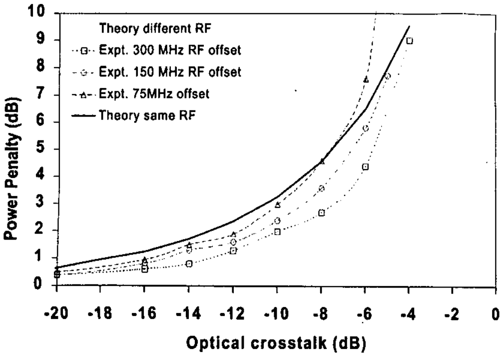

Fig. 4. Measured and predicted optical power penalties due to in-band optical crosstalk with different electrical frequencies.

B. Out-of-band Crosstalk

Although the case of out-of-band crosstalk results in power penalties which are identical to those predicted using an electrical interference analysis, it should be noted that a –30 dB optical crosstalk level corresponds to an electrical crosstalk level of –60 dB. Furthermore, while the crosstalk signal cannot be rejected for baseband data modulation, in the case of IF/RF modulation where some or all of the crosstalk is at a different electrical frequency, electrical filtering allows the crosstalk to be further attenuated. If both the crosstalk channel is at a different RF frequency and perfect electrical filtering is possible, then no penalty would be observed, even at 0 dB of out-of-band optical crosstalk (assuming that the wavelengths are sufficiently separated and mixing terms fall outside the optical receiver bandwidth).

V. DISCUSSION AND CONCLUSIONS

A comparison of in-band and out-of-band power penalties indicates that in-band optical crosstalk is of greater significance for signal impairments in fiber-radio WDM networks. If in-band optical crosstalk occurs between electrical signals at different frequencies, then an optical power penalty corresponding to the best case for identical wireless frequencies will result, even for perfect electrical filtering. This changes the total crosstalk level required to produce a 1 dB optical power penalty from –17 dB to –13.5 dB. These results illustrate the important difference between baseband crosstalk and IF/RF crosstalk: while baseband crosstalk results in an overlap in the electrical frequency domain, IF/RF modulation allows the use of multiple frequencies, some or all of which may be different. This together with the use of WDM should allow the impact of optical crosstalk in fiber-radio networks to be minimized through the use of appropriate optical wavelengths and electrical frequency planning.

In conclusion, we have presented experimental results showing the impact of in-band optical crosstalk in fiber-radio WDM networks. We have considered the possibility of the crosstalk channel carrying a signal at a different electrical frequency and shown how this reduces the resulting optical power penalties. However, these are still significantly higher than those observed for out-of-band crosstalk even assuming perfect filtering of the crosstalk electrical channel. These results show the advantages of IF/RF modulation techniques for radio-over-fiber delivery from a crosstalk point of view and the importance of both optical and electrical frequency assignments.

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