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Performance of Manchester-Coded Payload in an Optical FSK Labeling Scheme

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Abstract—The modulation crosstalk between combined frequency-shift keying (FSK) and intensity modulation (IM) in an optical label-switching network is analyzed both theoretically and experimentally. A comparison between the performance of nonreturn-to-zero (NRZ) and Manchester-coded payload is made. It is shown that Manchester coding of the payload helps to suppress the crosstalk introduced into the optical FSK label, thus achieving better network performance than NRZ coding.

Index Terms—Crosstalk, modulation coding, optical frequency-shift keying (FSK), optical label switching.

I. INTRODUCTION

ALL-OPTICAL label switching implements the packet routing and forwarding functions of multiprotocol label switching directly in the optical layer, which is a promising technology for the next-generation networks. Several optical labeling methods have been proposed [1], and optical frequency-shift keying (FSK) labeling is regarded as a feasible solution [2], [3].

In the FSK labeling scheme [2], the label information is impressed upon the optical frequency of a light signal through FSK modulation, while the payload information is added on the light intensity through intensity modulation (IM). In this way, an optically labeled packet is formed.

However, it has been shown that IM of the payload introduces crosstalk to the FSK label, resulting in intensity fluctuation of the detected label signal [4]. Therefore, the network scalability is greatly limited. In this letter, we propose and demonstrate the use of the Manchester-coding technique to reduce such modulation crosstalk. Manchester coding has been employed in certain network applications instead of commonly used nonreturn-to-zero (NRZ) coding [5].

In Section II, a theoretical analysis is carried out to investigate the modulation crosstalk, and the effect of modulation format of the payload on the label detection is analyzed. In Section III, we experimentally investigate the labeling performance in the presence of Manchester-coded (MC) payload. In Section IV, summarizing conclusions are given.

II. THEORETICAL ANALYSIS

Fig. 1 illustrates a transmission link in an optical FSK label-switching network. At ingress edge nodes, internet protocol (IP)
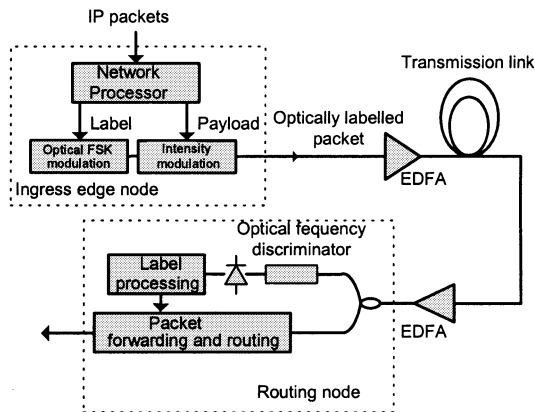
Fig. 1. Transmission link in an optical FSK label-switching network.

packets are processed in an adaptation layer that encapsulates payload with the corresponding label data. The high-speed payload data is transmitted by IM, while the moderate-speed label data is transmitted on the same lightwave by optical FSK modulation. Thus, an optically labeled packet can be generated. At an intermediate routing node, the label can be extracted using optical FSK demodulation. Based on the detected label, core routers can perform the routing and forwarding functions. The robustness of such an FSK labeling scheme in a label-swapping node has already been demonstrated [2], [6].

The optical field of a labeled packet can be described as

$$X(t) = E_0\sqrt{1 + mP(t)}\exp\left(i\left(\omega_0 t + \frac{\Delta\omega_f}{2}\int_{-\infty}^{t} L(t)dt\right)\right).$$

Here, E_0 represents the field amplitude, $P(t)$ the payload data, $L(t)$ the label data, ω_0 the optical frequency, $\Delta\omega_o$ the frequency deviation value, and m the IM depth. Both $P(t)$ and $L(t)$ are assumed to have square elementary data waveforms varying in the range of $[-1, 1]$.

At the receiving node, the payload information can be perfectly detected using a photodiode, while an optical FSK discriminator is employed to perform FSK/amplitude-shift keying conversion to detect the label. A Mach–Zehnder interferometer filter or the edge of an optical bandpass filter can be used to perform the frequency discriminating function. We reasonably assume that the transfer function of the discriminating filter is linear around the carrier frequency and can be written

$$T(\omega) = 1 + k(\omega - \omega_0) \qquad (2)$$

where k determines the slope of the filter edge.

Thus, the discriminated output field becomes

$$E'(t) = E(t) - ik\frac{d}{dt}\left[X(t)\exp(-i\omega_0 t)\right]. \qquad (3)$$

According to (1)–(3), the optical intensity of the detected label can be derived, which is approximately given by

$$Y(t) = Y_0 \left(1 + mP(t)\right)\left(1 + nL(t)\right) \qquad (4)$$
$$\text{where} \quad n = \frac{k\Delta\omega_f}{\left(\frac{1+k^2\Delta^2\omega_f}{4}\right)}$$

and n determines the extinction ratio (ER) of the discriminated output. In the derivation, we assume that the payload bandwidth is much smaller than the frequency deviation induced by FSK, thus, the payload $P(t)$ is not affected by the frequency discriminator.

Assuming 50% mark-density random data, we have

$$E\langle P(t)\rangle = E\langle L(t)\rangle = 0. \qquad (5)$$

The autocorrelation function of $Y(t)$ is then given by

$$\begin{aligned}
R(t, t+\tau) &= E\left(Y(t)Y(t+\tau)\right)\\
&= Y_0^2 \left(1 + n^2 E\langle L(t)L(t+\tau)\rangle\right.\\
&\quad + m^2 E\langle P(t)P(t+\tau)\rangle\\
&\quad + m^2 n^2 E\langle P(t)P(t+\tau)\rangle\\
&\quad \left.\times E\langle L(t)L(t+\tau)\rangle\right).
\end{aligned} \qquad (6)$$

According to (6), the power spectral density (PSD) of the discriminated output is given by

$$\begin{aligned}
S(\omega) = Y_0^2 \left[\delta(\omega) + n^2 L_p(\omega) + m^2 P_p(\omega)\right.\\
\left. + m^2 n^2 L_p(\omega) \otimes P_p(\omega)\right]
\end{aligned} \qquad (7)$$

where $L_p(\omega)$ and $P_p(\omega)$ represent the PSD of the label and the payload, respectively. As indicated by (7), the IM of the payload induces two crosstalk components that stem from spectral overlap with the label in the spectrum, hence degrading the label receiving performance.

To evaluate the modulation crosstalk, we define a signal-to-noise ratio (SNR) parameter according to

$$\text{SNR} = \frac{\int_0^{\omega_l} L_p(\omega)d\omega}{m^2\int_0^{\omega}\left[\left(\frac{1}{n}\right)^2 P_p(\omega) + L_p(\omega)\otimes P_p(\omega)\right]d\omega} \qquad (8)$$

where ω_l is the effective bandwidth of the label receiver.

Equation (8) indicates that the overlap area between the payload and label spectrum is important in determining the SNR value. Therefore, we could encode the payload and the label in different formats in order to decrease the overlap area, thus achieving a high SNR.

Manchester coding presents one possible solution. Compared with NRZ, Manchester coding employs the transition edges to carry the information and pushes much spectral power into the high frequency region. Therefore, an MC payload will have much less spectral overlap with the label, hence, improving the SNR at the label receiver.
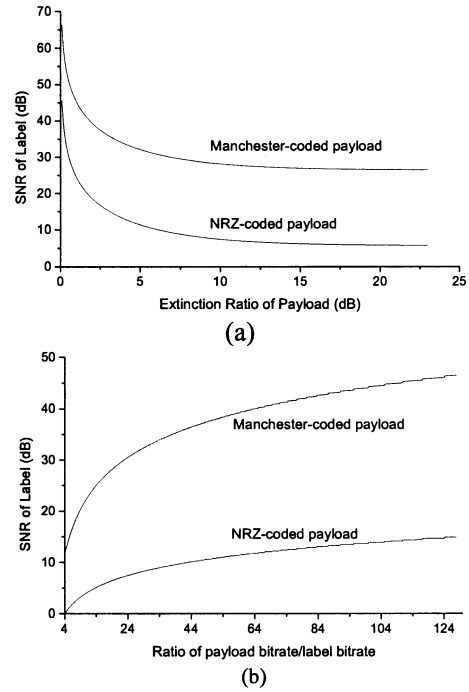

Fig. 2. SNR performance of label in the presence of NRZ/MC payloads.

The PSD in the NRZ case is given by

$$P(\omega) = T\frac{\sin^2\left(\frac{\omega T}{2}\right)}{\left(\frac{\omega T}{2}\right)^2} \qquad (9)$$

while the PSD in Manchester case is given by

$$P(\omega) = T\frac{\sin^4\left(\frac{\omega T}{4}\right)}{\left(\frac{\omega T}{4}\right)^2} \qquad (10)$$

where T represents the period of bit sequence.

Through (8)–(10), we compare the performance of the MC payload and the NRZ payloads and plot the results in Fig. 2. In calculation of Fig. 2(a), the ratio of payload bit rate to label bit rate is set to be 16. It shows that the SNR of the label is strongly degraded by a high-modulation-depth NRZ payload. Therefore, the ER has to be kept at low value to ensure acceptable label detection. On the other hand, the SNR value is improved more than 20 dB through Manchester coding, hence, overcoming the limitations on ER. Such an SNR improvement is also observed for other bit-rate ratios, and it is even enhanced at a lower label bit rate, as indicated in Fig. 2(b). In the calculations for Fig. 2(b), the ER of payload is set to 20 dB while the FSK discriminator performs an ideal operation, e.g., $n = 1$.

III. EXPERIMENTAL RESULTS

In order to investigate the performance of combined FSK and IM in an optical labeling scheme, we have experimentally set up an optical link, as shown in Fig. 3.

Two pseudorandom pattern generators were used to generate the payload and label information. A directly modulated distributed feedback (DFB) laser integrated with an electroabsorption (EA) modulator performed the optical FSK modulation [4]. Direct modulation of the DFB laser generates the 622-Mb/s optical FSK signal combined with residual IM.
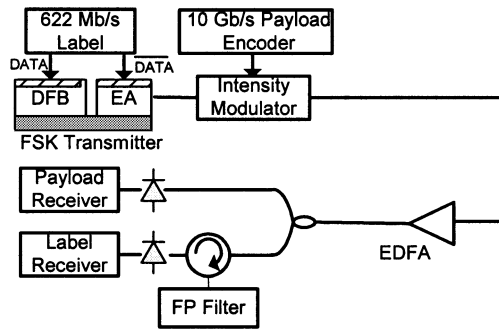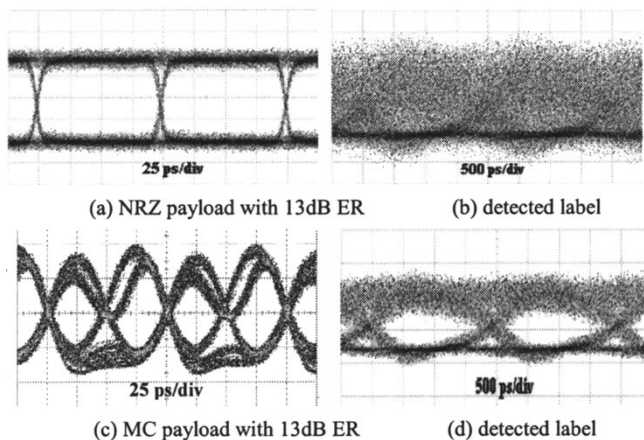
Fig. 3.   Experimental setup.

Fig. 5.   BER performance of the extracted label in the presence of MC payload.

Fig. 4.   Eye diagrams of extracted label in the presence of NRZ/MC payload.

Fig. 6.   RF power spectrum of extracted label in the presence of (a) NRZ payload and (b) MC payload with 13-dB ER.

However, by driving the EA with the inverted label data, the residual IM is removed. The FSK tone spacing was set to be 20 GHz. The payload information is then added through a dual-electrode Mach–Zehnder modulator operating at 10 Gb/s. This modulator exhibits nearly chirp-free performance through the push–pull configuration. At the receiver node, the labeled signal was split using a 3-dB optical coupler. The signal in one arm was directly detected by a photodiode and, thus, the optical payload was converted into the electrical domain. In the other arm, a Fabry–Pérot (FP) filter with 20-GHz full-width at half-maximum bandwidth was used to achieve the FSK demodulation. The FP filter exhibits a high contrast ratio when it operates in the reflection mode. The demodulated label was then received by an electrical receiver with 600-MHz bandwidth.

Fig. 4 shows the eye diagrams of the detected label in the presence of NRZ and MC payloads. With the 13-dB ER NRZ payload, the detected label is greatly distorted and does not exhibit error-free performance. On the other hand, with the MC payload having the same ER, the detected label has a large eye opening resulting in error-free performance. The results of bit-error-rate (BER) measurements shown in Fig. 5 indicate that adding the FSK label to the MC payload results in nearly 3.2-dB power penalty.

In Fig. 6, the measured radio-frequency (RF) power spectra of the extracted labels provide further information on the modulation performance. With the NRZ payload, much of the label power is loaded with noise induced by the payload modulation, thus, the SNR has a poor value of only 4 dB; with the Man-
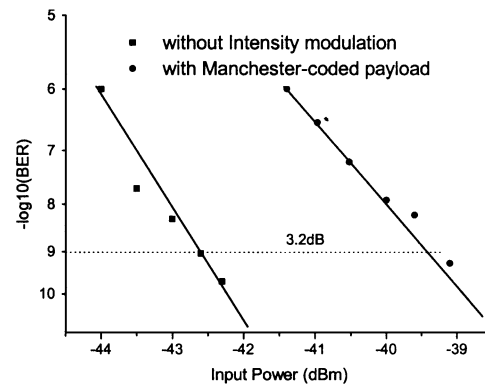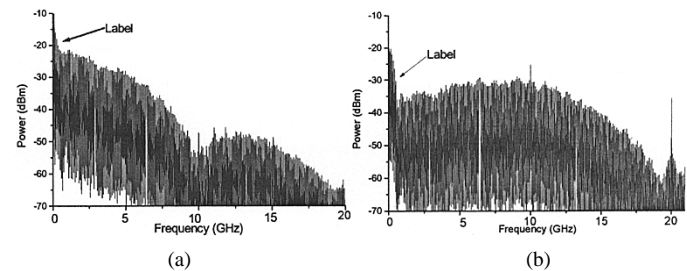
chester payload, the label can be distinguished by nearly 20 dB, thus allowing much better receiver performance. However, compared with the conventional NRZ signal format, both FSK modulation and Manchester coding broaden the signal spectrum to some extent. Therefore, more stringent dispersion requirements will be imposed on the transmission link.

IV. Conclusion

The modulation crosstalk between the label and the payload presents a limitation to the FSK/IM label-switched network. We have theoretically shown that such a limitation can be overcome by adopting the Manchester-coding technique. The experimental results also confirm the theoretical analysis.

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