Equalization in Coherent Lightwave Systems Using a Fractionally Spaced Equalizer

JACK H. WINTERS, SENIOR MEMBER IEEE

***Abstract*—Chromatic dispersion in coherent-detection lightwave systems is a linear distortion in the electrical signal at the receiver that can be equalized by linear equalization techniques. Here we consider the performance of a fractionally spaced analog tapped delay line equalizer that has the advantages of being adaptive, capable of also equalizing other linear distortions (such as polarization dispersion and nonideal receiver response), and eliminating chromatic dispersion over any distance if a sufficient number of taps are used. We show how this equalizer can be implemented at IF and at baseband (for homodyne detection). Results show that an N-tap equalizer increases the maximum bit rate distance B^2L approximately $(N-1)/2$ fold (e.g., a threefold increase in distance with a seven-tap equalizer).**

I. Introduction

Signal dispersion is a major factor limiting the maximum distance and/or bit rate of long-haul fiber-optic systems. Chromatic dispersion is usually the dominant impairment, but polarization dispersion and nonideal receiver response can also limit the bit-rate distance. However, in a coherent detection system, all these distortions are linear in the electrical signal at the receiver (chromatic dispersion is nonlinear with direct detection) and, therefore, can be equalized by linear electrical filtering techniques.

Previous papers have considered linear equalization techniques for chromatic dispersion [1]–[4], polarization dispersion [4], [5], and nonideal receiver response [4], [6]. Chromatic dispersion is the easiest to equalize because the dominant type (first order) is a fixed linear delay distortion (polarization dispersion varies with time and both polarization dispersion and nonideal receiver response can have higher order delay and amplitude distortion). Devices that have been studied for chromatic dispersion equalization include microstrip lines [1], microwave waveguides [2], all pass lattice filters [3], and synchronous tapped delay lines [4]. Microstrip lines and microwave waveguides have the advantage that they have simple structures that can be easily implemented and can increase the dispersion-limited distance several fold. However, they must be built to precisely match the chromatic dispersion-length product of the fiber (i.e., they are not adaptive), which can be difficult with large dispersion. Also, they equalize only linear delay distortion (i.e., they cannot equalize polarization dispersion or nonideal receiver response[1]). All pass filters can also increase the chromatic dispersion-limited bit-rate distance several fold (an N fold increase with a $4N$ section filter [3]), but can equalize only delay distortion. A synchronous tapped delay line, however, can equalize any type of linear distortion and can easily be made adaptive [4] to track polarization dispersion and changes in nonideal receiver response or other distortions due to aging, temperature variations, etc., and to allow for easy installation without manual tap weight adjustment. Unfortunately, a synchronous tapped delay line is limited in the extent that it can increase the bit-rate distance with chromatic dispersion—it can increase the dispersion-limited bit-rate distance by a maximum of about 60% (for a 1-dB optical power penalty). This is because, with a synchronous tapped delay line, signal delays are an integer multiple of the bit duration T. Thus, the equalizer frequency response is periodic with period $1/T$, while the signal spectrum usually extends beyond $1/T$, and aliasing (excess bandwidth) degrades the equalized signal. This problem can be eliminated by a fractionally spaced equalizer [7], where the tap spacings are less than T ($T/2$ is adequate for most lightwave systems). Thus, with a sufficient number of taps a fractionally spaced equalizer can eliminate chromatic dispersion for any bit-rate distance, while also reducing polarization dispersion and nonideal receiver response. It can also reduce the sensitivity of the detector to timing offset.

In this paper we study the equalization of chromatic dispersion in a coherent detection lightwave system by a fractionally spaced equalizer. We describe the equalizer and show how it can be implemented in both heterodyne and homodyne detection systems. Results show that a fractionally spaced equalizer (at baseband for homodyne and at IF for heterodyne detection) with N taps can increase the dispersion-limited bit-rate distance $(N-1)/2$ fold.

In Section II, we describe the equalizer. We present the analysis and results in Section III. A summary and conclusions are given in Section IV.

II. System

Fig. 1 shows a block diagram of an analog tapped delay line equalizer. The input signal is divided N ways, delayed by increments of βT, weighted and recombined to form the output signal. At gigabit-per-second data rates the delays can be implemented by short lengths of cable or transmission lines. The weights, which must be ad-

Manuscript received March 15, 1990; revised May 3, 1990.
The author is with AT&T Bell Laboratories, Holmdel, NJ 07733.
IEEE Log Number 9037057.

[1]That is, except for the linear delay portion of the distortion.

0733-8724/90/1000-1487$01.00 © 1990 IEEE

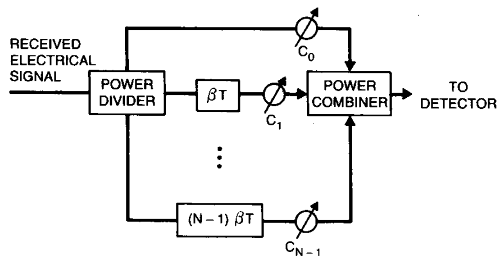


Fig. 1. Block diagram of an analog, fractionally spaced, tapped delay line equalizer.

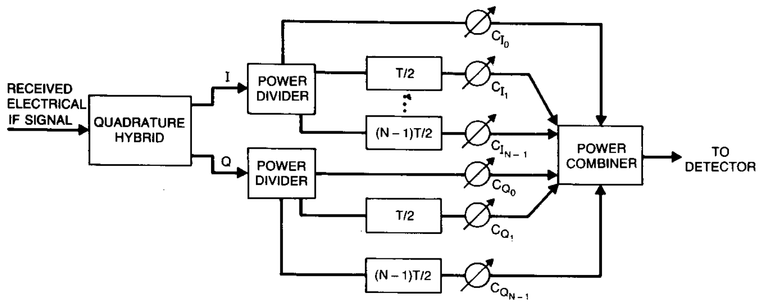


Fig. 2. Block diagram of a fractionally spaced equalizer operating at passband (IF).

justable for our application, can be implemented by variable attenuators or variable gain amplifiers. These attenuators or amplifiers need only have the same bandwidth as the detector preamplifier, at IF for heterodyne detection and at baseband for homodyne detection. The weights can be adjusted manually (for chromatic dispersion and constant nonideal receiver response) or electronically adjusted to adapt easily to any system or to track time varying impairments (such as polarization dispersion). Techniques for implementing adaptation algorithms are described in [4], where a simple technique is shown using the zero forcing algorithm for a synchronous ($\beta = 1$) equalizer. Implementation of the zero forcing algorithm for a fractionally spaced equalizer is discussed in [8].

As discussed in Section I, to avoid the excess bandwidth problem, the spacing of the taps βT must be less than the reciprocal of the maximum bandwidth of the signal. As stated previously, for most lightwave systems, a $T/2$ spacing is adequate.

With heterodyne detection, the electrical signal is at an IF frequency and the weights are complex valued. Thus, the weight elements must produce both a variable gain and phase shift. Alternatively (as shown in Fig. 2), a quadrature hybrid (Hilbert filter [7]) can be used, which divides the signal into in-phase and quadrature components. The weights in each of the two branches are then real-valued (i.e., gain only).

With homodyne detection, the electrical signal is baseband, and the weights are real-valued (i.e., gain only—only half the number of real-valued weights are required as in the passband equalizer). However, although such a baseband equalizer can equalize polarization dispersion, nonideal receiver response, and second-order chromatic dispersion, it cannot equalize first-order chromatic dispersion, because the inverse filter weights are not real-valued. Specifically, with first-order chromatic dispersion, the fiber transfer function is given by

$$H_c(f) = e^{-j\alpha f^2}, \qquad \alpha = \pi D(\lambda)\frac{\lambda^2}{c}L \tag{1}$$

where L is the fiber length, $D(\lambda)$ is the linear delay coefficient (e.g., $D(\lambda) = 17$ ps/km/nm for a 1.55-μm signal in a standard fiber), and λ is the wavelength. Thus, the inverse filter

$$H_{EQ}(f) = H_c^{-1}(f) = e^{j\alpha f^2} \neq H_{EQ}^*(-f) \tag{2}$$

and the impulse response of the filter is complex. Therefore, the inverse filter cannot be realized by a baseband equalizer using only one baseband received signal. However, with phase-diversity homodyne detection [9], the received optical signal is split and mixed with the local oscillator and a 90° phase-shifted local oscillator, and, therefore, both in-phase and quadrature components of the received optical signal are generated at baseband. Fig. 3 shows a block diagram of the homodyne detector with phase diversity. Cross coupled baseband fractionally spaced equalizers on the in-phase and quadrature electrical baseband signals can now equalize the chromatic dispersion (i.e., QAM equalization [7]). Note that this baseband equalizer has the same performance as the passband equalizer (Fig. 2) but uses twice the number of real-valued weights. However, the variable gain amplifiers or attenuators need only operate (from dc) up to the baseband

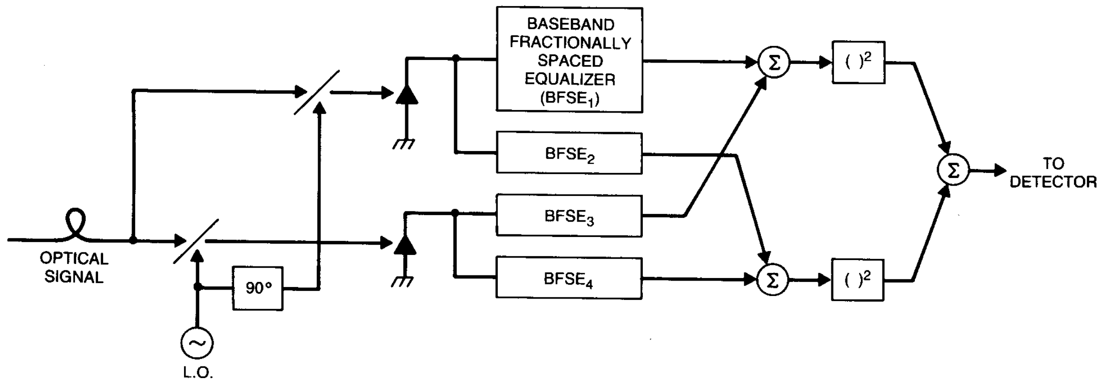


Fig. 3. Block diagram of a fractionally spaced equalizer operating at baseband.

signal bandwidth (the data rate), as opposed to at least twice the data rate in the passband equalizer.

Note that if we mix the homodyne baseband electrical signals (in-phase and quadrature) with a local oscillator, we can use a passband equalizer as in heterodyne detection (i.e., the equalizer of Fig. 2 without the quadrature hybrid). This may be advantageous if passband components operating at higher frequency are preferable to lower frequency components that must operate down to (nearly) dc. Note, however, that passband operation is merely an option with the fractionally spaced equalizer, whereas passband operation (conversion to IF) is required with the microwave waveguide or microstrip line equalizers.

Implementation of a fractionally spaced equalizer at gigabit-per-second data rates is relatively easy ([4], see also [5] and [6] which describe equalizers at 1.1 and 8 Gb/s, respectively). The delays can be implemented by transmission lines or coaxial cables, and the weights by variable attenuators. Voltage variable attenuators (for adaptation), operating from dc to 18 GHz, are commercially available at low cost. Power dividers/combiners and amplifiers (if needed), operating from dc to above 10 GHz are also commercially available, although amplifiers operating down to dc cost significantly more than passband amplifiers.

III. Analysis and Results

Let us now consider the effect of chromatic dispersion on the optical-power penalty (eye closure). The level of dispersion in the channel over the bandwidth (data rate) B can be expressed in terms of the chromatic dispersion index γ, given by [10]

$$\gamma = \frac{1}{\pi} B^2 L D(\lambda) \frac{\lambda^2}{c} \tag{3}$$

or, from (1)

$$\gamma = \alpha \left(\frac{B}{\pi}\right)^2. \tag{4}$$

The level of intersymbol interference (and therefore the optical-power penalty) for given γ depends on the modulation and pulse shape. In [10], the optical-power penalty versus γ was shown for CPFSK, MSK, PSK, ASK, and DPSK with rectangular pulses. The power penalty is lowest with DPSK, but PSK and ASK have nearly the same penalty. In particular, for a 1-dB optical-power penalty, γ is approximately 0.23 for DPSK and 0.22 for PSK or ASK. It was shown in [4] that with ASK this index can be increased slightly to 0.24 if rounded pulses are used rather than rectangular pulses. Therefore, in this paper, we will consider ASK modulation with rounded pulses, although our results can easily be extended to other modulations and/or pulse shapes. Specifically, our results were generated by computer simulation using the model of [4]. That is, the transmitted signal is

$$X(t) = \sum_k a_k P(t - kT) \tag{5}$$

where $a_k = 0$ or 1, and T is the bit duration ($T = 1/B$), and

$$P(t) = \begin{cases} 0.5\left(\dfrac{t + 0.85T}{0.35T}\right)^2 & -0.85T \le t < -0.5T \\ 1 - 0.5\left(\dfrac{t + 0.15T}{0.35T}\right)^2 & -0.5T \le t < -0.15T \\ 1 & -0.15T \le t < 0.15T \\ 1 - 0.5\left(\dfrac{t - 0.15T}{0.35T}\right)^2 & 0.15T \le t < 0.5T \\ 0.5\left(\dfrac{0.85T - t}{0.35T}\right)^2 & 0.5T \le t \le 0.85T. \end{cases} \tag{6}$$

The transmit data consist of a repetitive pseudorandom data stream of length 64, which contains all bit sequences of length 6. Thus, the results are accurate as long as the main portion of the intersymbol interference due to chromatic dispersion extends over less than 7-b periods. The receiver filter is a 3-pole Butterworth filter with a bandwidth of 70% of the data rate ($0.7B$).

Fig. 4 shows the optical-power penalty versus the chromatic dispersion index with a fractionally spaced equalizer with several different number of taps. Results are also shown for the system without equalization ($N = 1$) and with a synchronous linear equalizer with 11 taps[2] (LE). The fractionally spaced equalizer with only 4 taps is shown to have about the same penalty as a synchronous equalizer. Note also that, with more than 8 taps, the fractionally spaced equalizer eliminates the chromatic dispersion penalty even for indexes where the eye is closed without equalization.

Fig. 4 shows that, for a given optical-power penalty, the chromatic dispersion index increases linearly with the number of taps. This is shown explicitly in Fig. 5 for a 2-dB penalty. From this figure, it can be seen that the chromatic dispersion index is approximately given by

$$\gamma \doteq \begin{cases} 0.32, & N = 1, 2 \\ 0.32 \dfrac{(N-1)}{2}, & N > 2 \end{cases} \quad (7)$$

where N is the number of taps in the equalizer. Thus with $N > 2$, the fractionally spaced equalizer increases the index $(N-1)/2$ fold. Specifically, with every addition of 2 taps (corresponding to an additional coverage of intersymbol interference of T) the equalizer eliminates intersymbol interference (due to chromatic dispersion) over an additional bit period. Thus, with a sufficient number of taps[3] a fractionally spaced equalizer eliminates any amount of (first-order) chromatic dispersion. For example, at 1.55 μm in a standard (single-mode) fiber with a dispersion minimum at 1.3 μm ($D(\lambda) \doteq 17$ ps/km/nm), a 9-tap fractionally spaced equalizer increases the maximum B^2L from 5500 to 22 000 $(\text{Gb/s})^2$km.

If the first-order chromatic dispersion is equalized (or signals are transmitted at the chromatic dispersion minimum of the fiber), then the second-order chromatic dispersion must be considered and may need to be equalized. The channel transfer function with second-order chromatic dispersion is given by (following the method given in [10] for first-order chromatic dispersion)

$$H_c(f) = e^{-j\alpha_2 f^3} \quad (8)$$

where

$$\alpha_2 = \frac{\pi}{3} D'(\lambda) \frac{\lambda^4}{c^2} L \quad (9)$$

and $D'(\lambda)$ is the quadratic delay coefficient (e.g., $D'(\lambda) \approx 0.05$ ps/km/nm^2 at 1.55 μm in a dispersion-shifted fiber). The second-order chromatic dispersion index is then given by

$$\gamma_{2\text{nd}} = \frac{1}{3\pi^2} B^3 L D'(\lambda) \frac{\lambda^4}{c^2}. \quad (10)$$

Note that

$$H_{EQ}(f) = H_c^{-1}(f) = e^{j\alpha_2 f^3} = H_{EQ}^*(-f). \quad (11)$$

Thus, second-order chromatic dispersion can be equalized by a baseband equalizer with only N real-valued weights (i.e., Fig. 1 with real-valued c_i—half the number of weights used with heterodyne detection). With phase-diversity homodyne detection, however, separate baseband equalizers are required on the in-phase and quadrature baseband electrical signals (i.e., Fig. 3 without $BFSE_2$ and $BFSE_3$—the same number of weights used with

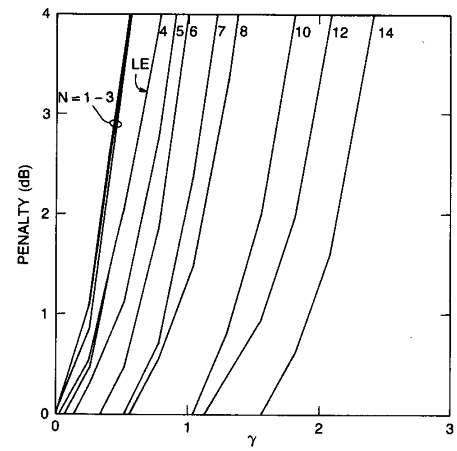


Fig. 4. Optical-power penalty versus chromatic dispersion index with an N-tap fractionally spaced equalizer. Results without equalization ($N = 1$) and with an 11-tap synchronous linear equalizer (LE) are also shown.

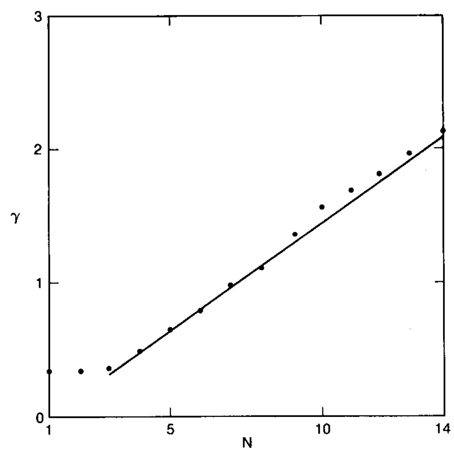


Fig. 5. Chromatic dispersion index with a 2-dB optical-power penalty versus the number of taps in a fractionally spaced equalizer. Calculated results (points) are compared to the $0.16(N-1)$ approximation (solid line).

[2]The performance of this equalizer does not improve with more than 5 taps.

[3]In practice, with large chromatic dispersion, a microstrip line or microwave waveguide (which would equalize most of the chromatic dispersion) would be used in combination with the fractionally spaced equalizer. This combination would have all the advantages of the fractionally spaced equalizer, without requiring a large number of taps.

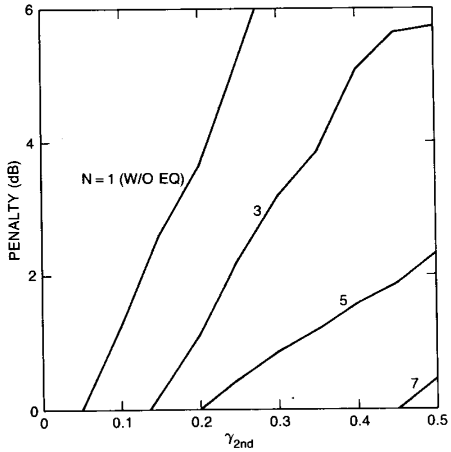


Fig. 6. Optical-power penalty versus the second-order chromatic dispersion index with an N-tap fractionally spaced equalizer. Results without equalization are also shown.

heterodyne detection). In most cases, though, first-order chromatic dispersion must also be equalized, and therefore the equalizer shown in Fig. 3 (which requires twice the number of weights used in heterodyne detection) would still be required.

Fig. 6 shows the optical-power penalty versus the second-order chromatic dispersion index with a fractionally spaced equalizer with 1 (i.e., without equalization), 3, 5, and 7 taps. The second-order chromatic dispersion index (for a given penalty) is increased approximately twofold with 3 taps, fourfold with 5 taps, and more than sixfold with 7 taps. Thus, the index appears to increase at least as fast as linearly with the number of taps ($\approx (N-1)$-fold for $3 \leq N \leq 7$), and we might expect that, as with the first-order chromatic dispersion index, the second-order chromatic dispersion index could be increased to any value with a sufficient number of taps. However, at least in systems in the foreseeable future, the required an increase in the second-order chromatic dispersion index should be small. For example, at 1.55 μm in a dispersion-shifted fiber, with $D'(\lambda) = 0.05$ ps/km/nm^2, the second-order chromatic dispersion limited B^3L is approximately 9×10^8 (Gb/s)^{3}km (corresponding to $\gamma_{2nd} = 0.1$) without equalization. Thus, even for the longest undersea system (10 000 km), second-order chromatic dispersion will not be a problem (i.e., penalty > 1 dB) unless $B > 43$ Gb/s. In such a 10 000-km system, though, a 3-tap equalizer eliminates the 1-dB penalty at 45 Gb/s, and a 7-tap equalizer permits a doubling of the data rate with the elimination of the 1-dB penalty.

IV. Conclusions

In this paper we have studied the equalization of chromatic dispersion by a fractionally spaced analog tapped delay line. We showed that this equalizer can be implemented at IF for heterodyne detection and at baseband for homodyne detection. This equalizer has the advantages that it is adaptive and can also equalize other impairments such as polarization dispersion and nonideal receiver response. Computer simulation results show that, with a sufficient number of taps, any amount of chromatic dispersion can be eliminated. For example, with first-order chromatic dispersion, the maximum B^2L can be increased $(N-1)/2$ fold $(N > 2)$ with an N-tap equalizer.

References

[1] N. Takachio and K. Iwashita, "Compensation of fibre chromatic dispersion in optical heterodyne detection," *Electron. Lett.*, pp. 108–109, Jan. 21, 1988.

[2] J. H. Winters, "Equalization in coherent lightwave systems using microwave waveguides," *J. Lightwave Technol.*, vol. 7, pp. 813–815, May 1989.

[3] P. G. Priest and T. G. Giallorenzi, "Dispersion compensation in coherent fiber-optic communications," *Opt. Lett.*, vol. 12, pp. 622–624, Aug. 1987.

[4] J. H. Winters and R. D. Gitlin, "Electrical signal processing techniques in long-haul fiber-optic systems," in *Proc. Int. Conf. Commun., '90*, pp. 305.3.1-7; to appear in *IEEE Trans. Commun.*

[5] J. H. Winters and M. Santoro, "Experimental equalization of polarization dispersion," in *Proc. Conf. Lasers and Electro-Optics '90*; also in *Photon. Lett.*, to be published.

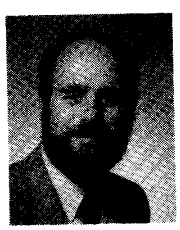
[6] A. H. Gnauck *et al.* "Information-bandwidth-limited transmission at 8 Gbit/s over 68.3 km of single-mode fiber," in *Tech. Dig. OFC '86* (Atlanta, GA), Feb. 24-26, 1986, paper PDP9.

[7] R. D. Gitlin and S. B. Weinstein, "Fractionally spaced equalization: an improved digital transversal equalizer," *Bell Syst. Tech. J.*, vol. 60, pp. 275–296, Feb. 1981.

[8] C. A. Siller, Jr. and W. Debus, "A Nyquist-rate adaptation algorithm for fractionally spaced equalizer," in *Proc. of Globecom '88*, Nov. 28-Dec. 1988, pp. 35.1.1-6.

[9] T. Okoshi and S. Yamashita, "Double-stage phase-diversity (DSPD) optical receiver: A new scheme having the advantages of heterodyning and homodyning," in *Postdeadline Papers of OFC '89*, 1989, paper PD19.

[10] A. F. Elrefaie, R. E. Wagner, D. A. Atlas, and D. G. Daut, "Chromatic dispersion limitations in coherent lightwave transmission systems," *J. Lightwave Technol.*, vol. 6, pp. 704–709, May 1988.



Jack H. Winters (S'77–M'82–SM'88) received the B.S.E.E. degree from the University of Cincinnati, Cincinnati, OH, in 1977 and the M.S. and Ph.D. degrees in electrical engineering from Ohio State University, Columbus, in 1978 and 1981, respectively.

Since 1981 he has been with AT&T Bell Laboratories in the Network Systems Research Department, Holmdel, NJ. His current work involves the study of equalization, interference cancellation, and coding techniques for direct and coherent detection lightwave systems.

Dr. Winters is a member of Sigma Xi.