A Near-Optimum Discriminator Demodulator for Binary FSK with Wide Tone Spacing

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***Abstract*—Optical FSK communication systems often require large tone spacings to reduce bit-error rate (BER) degradation from laser linewidth induced crosstalk. Until now, discriminator detection of FSK for such wide tone spacings has fallen short of matched filter performance because of the suboptimal choice of a prefilter. A near-optimum demodulator for 240 Mbps, 3-times minimum orthogonal CPFSK, has been constructed, with a measured performance that is 0.5 dB from matched filter theory at 10^{-9} BER. The design can be scaled to other data rates and tone spacings. The demodulator incorporates a novel frequency tracking loop that has good performance at low signal levels and no data-pattern dependence.**

I. Introduction

It has been shown recently that a delay-line discriminator design for demodulation of binary FSK can be optimized to provide matched-filter performance for any integral multiple of minimum orthogonal tone spacing [1]. In this letter, we describe a practical implementation of the prefilter with a measured performance within 0.5 dB of the matched-filter optimum. The prefilter response is synthesized by a cascade of two 2-pole Butterworth bandpass filters followed by a tapped-delay line.

Our application is in coherent optical communications, operating at 240 Mbps with three times minimum orthogonal tone spacing. (Direct modulation of laser diodes actually produces continuous-phase FSK, CPFSK, where our tone spacing corresponds to the modulation index, $h = 3$.) The large tone spacing is necessary to reduce bit-error rate (BER) degradation from laser linewidth-induced crosstalk. The design can be scaled to other data rates and tone spacings.

II. Prefilter Design

The optimum sine-wave impulse response was approximated by the impulse response from two 2-pole Butterworth bandpass filters separated by an ideal buffer amplifier and cascaded with a tapped-delay line (transversal) filter. The cascade of 2-pole Butterworth filters has an impulse response approximating a half-sinewave pulse. The tapped-delay line repeats the pulse N times to form the complete impulse response for N-times minimum orthogonal FSK. For our application, $h = 3$ CPFSK, the first repetition of the impulse response was added out-of-phase with the original, and delayed by approximately one-third of the symbol length, T. The second repetition was delayed by approximately two-thirds T, and added in-phase with the original response. The normalized baseband filter bandwidths were 2.238 Hz and 3.5 Hz. The bandpass filter bandwidths were twice the baseband filter widths scaled to the actual data rate. The tap spacing used was 0.319 T.

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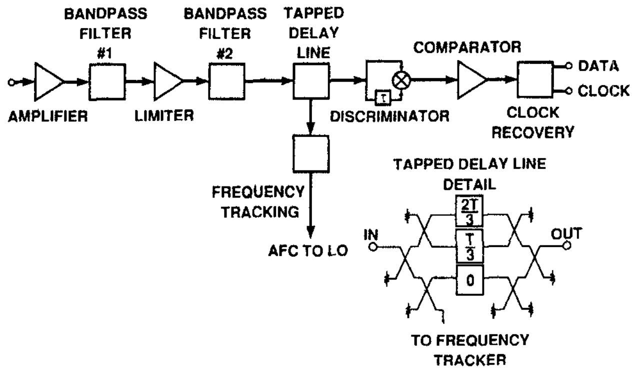

Fig. 1. Demodulator block diagram.

The demodulator performance was computer simulated to determine the effect of discriminator delay on bit-error rate. The optimum delay was found to be 0.157 T for this particular prefilter with $h = 3$, CPFSK. The degradation from matched-filter performance was predicted to be less than 0.1 dB at this point. The best realized performance was achieved with a delay of 0.075 T that had a measured sensitivity of 0.5 dB from matched-filter theory.

III. Implementation

The demodulator was constructed for 240 Mbps $h = 3$, CPFSK modulation using microstrip hybrid integrated circuits on alumina substrates. A block diagram of the demodulator is shown in Fig. 1. The 2-pole Butterworth bandpass filters were constructed in microstrip using shorted 1/4-wave transmission-line stubs. The tapped-delay-line filter was constructed using Lange 90 degree hybrid couplers and microstrip delay lines integrated on a single alumina substrate. A 1.25-dB pad was included in the shortest delay path to equalize the path loss with the longer delays. The delay-line discriminator was built by integrating a 13-dB directional coupler, a delay line, and a packaged double-balanced mixer. SUPER COMPACT® PC [2] was used to model the microstrip components.

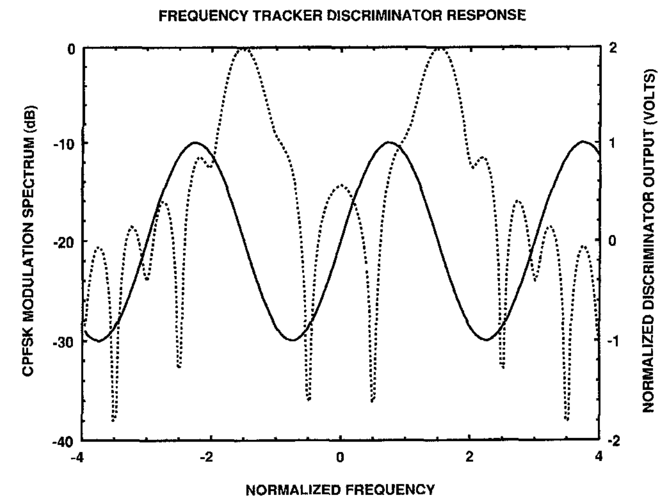

Fig. 2. Frequency tracker discriminator response. —— discriminator. - - - - CPFSK (without line spectra).

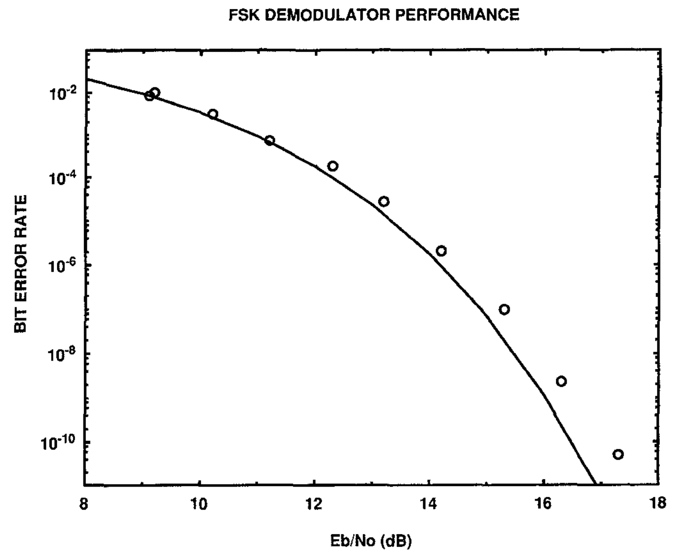

Fig. 3. FSK demodulator performance. —— FSK matched filter theory. o Measured performance.

Commercially available amplifiers and limiter amplifiers were used. The limiter amplifier had 35 dB of small signal gain which provided adequate demodulator dynamic range without the use of an AGC.

The two bandpass filters were separated by the limiter amplifier with the narrower filter placed before the limiter, and the wider filter placed after the limiter and just before the tapped-delay-line filter. Since the tapped-delay-line filter produces nulls in the passband response, this filter was placed after the limiter to avoid large fluctuations of the signal power at the input to the limiter that might result in distortion due to AM-to-PM conversion in the limiter amplifier. This configuration resulted in negligible loss in receiver sensitivity.

The output from the demodulator discriminator fed a hybrid clock-recovery circuit which provided outputs of unsynchronized data, synchronized data, and clock, all of which were at ECL levels with 200-ps transition times. The RMS clock jitter at high signal-to-noise ratios was 27 ps.

The demodulator was packaged within an equivalent board area of 7 by 7 inches.

IV. Frequency Tracker

Frequency tracking is important in optical systems where semiconductor lasers are sensitive to very small temperature and bias changes. Although in principle tracking can be achieved using the residual dc component out of the delay-line discriminator demodulator, proper tracking, in this case, requires very accurate symmetry in the frequency response of the demodulator components around the center IF frequency. Even then, the tracking signal is data pattern dependent, and the system can lose frequency lock during long strings of ones or zeros. These problems were overcome by using a second delay-line discriminator for frequency tracking. This discriminator was built with a delay of $T/3$, for $h = 3$, CPFSK, such that the cyclic response passed through a null at both of the tone frequencies as well as at the center IF. Fig. 2 shows the tracking discriminator response, without the effects of the prefilter, overlaying the spectrum of an $h = 3$, CPFSK modulated carrier. For convenience, the tracking discriminator was placed after the bandpass filters but before the tapped-delay line by using an available tap off of the tapped-delay line. The frequency tracker could have been placed after the tapped-delay line making optimum use of the signal available in the receiver.

The tracking loop acquired frequency at a carrier-to- noise-density ratio of approximately 72 dB-Hz, with low tracking offsets occurring above 82 dB-Hz. The threshold of communication was approximately 10 dB higher at 92 dB-Hz where tracking offsets were insignificant.

V. Performance

The demodulator was tested with a microwave source and a balanced modulator which produced a CPFSK modulated signal at the demodulator intermediate frequency. These measurements were used to characterize the demodulator in the absence of linewidth noise.

Fig. 3 shows the demodulator bit-error rate performance without laser linewidth noise as a function of E_b/N_o, the ratio of signal energy-per-bit to the noise density. The bit-error rate performance is 0.5dB from matched-filter theory at 10^{-9}, agreeing closely with the predicted performance for this demodulator.

VI. Conclusion

Several approximations have been made to the optimum prefilter design for a delay-line discriminator demodulator. These approximations have been shown to result in minimal performance degradation from an ideal matched-filter receiver, while achieving the simplicity and dynamic range of a limiter-discriminator demodulator. Theoretical calculations indicate a sensitivity within 0.1 dB of matched- filter theory is potentially achievable. A realized performance within 0.5

dB of matched-filter theory at a 10^9 bit-error rate has been attained.

A frequency tracker was also constructed using a separate delay-line discriminator which places nulls at the tone frequencies. The tracker has excellent noise performance and is insensitive to the data pattern.

The resulting demodulator is compact due to its simple architecture, but has performance near ideal matched-filter theory. The architecture can be used for other tone spacings by changing the number and location of taps on the tapped-delay line.

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References

[1] D. M. Boroson, "Optimal design of prefilters for binary FSK discriminators," *Electronic Lett.*, vol. 28, no. 3, pp. 284–286, Jan. 30, 1992.
[2] SUPER COMPACT® PC Ver. 4.1, Compact Software, Paterson, NJ.