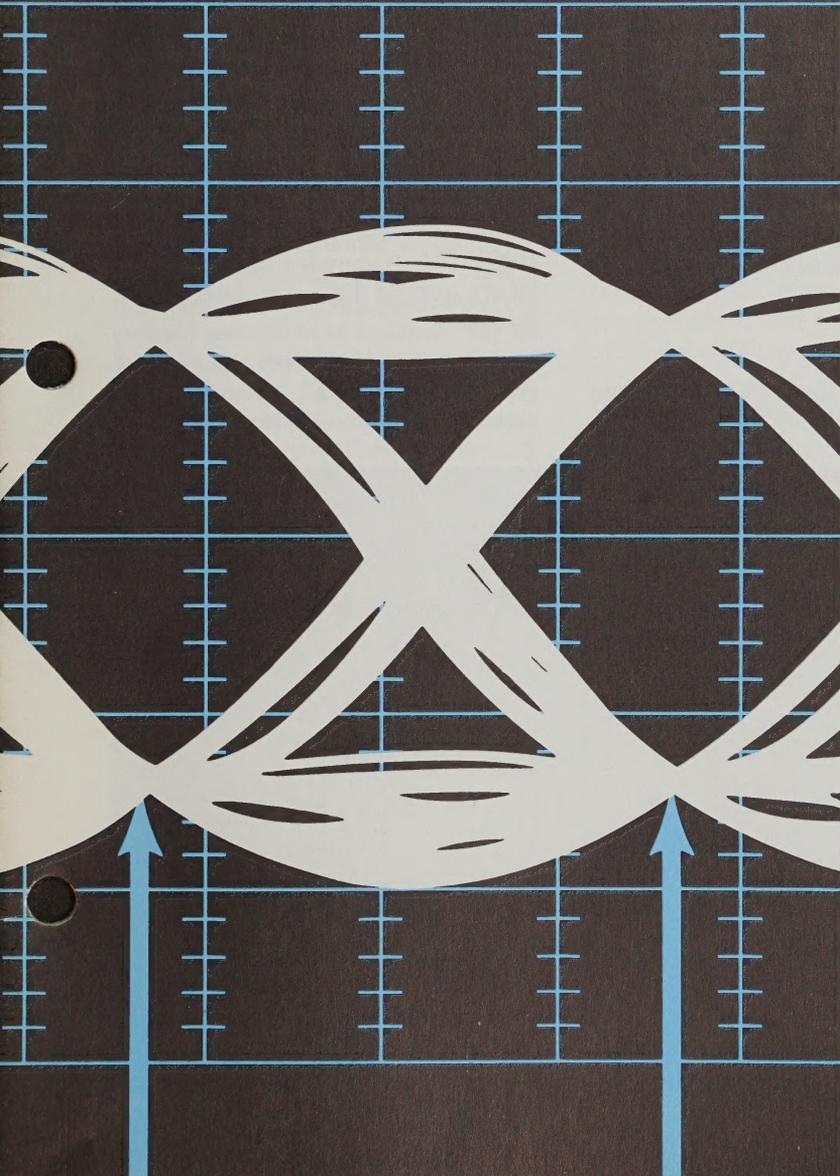


PSK Demodulation Part 1



WATKINS-JOHNSON COMPANY

Tech-notes

Developed during the early days of the deep space programs, phase-shift keying now finds widespread use in both military and commercial communication systems. For telemetry applications, PSK is considered an efficient form of data modulation because it provides the lowest probability of error for a given received signal level, when measured over one symbol period. Terrestrial microwave radio links and satellite communication systems also frequently employ PSK as their modulation format.

The purpose of this tutorial is to outline the various practical techniques used for PSK demodulation. Relative relationships, such as tradeoffs between cost, complexity, and performance are also discussed. In addition, ample references are provided the reader for elaboration on selected topics.

Definitions

Phase-shift keying (PSK) is a modulation process whereby the input signal,

a binary PCM waveform, shifts the phase of the output waveform to one of a fixed number of states. The signal can be written as

$$V_o(t) = \sqrt{2S} \text{Sin} \left[\omega_o t + \frac{2\pi(i-1)}{M} \right]$$

$$i = 1, 2, \dots, M$$

$$-T_s/2 \leq t \leq T_s/2$$

where, S = the average signal power over the signalling interval, T_s ,

$M = 2^N$ the number of allowable phase states

N = the number of bits needed to quantize M

Three common versions, binary or BPSK ($M=2$), quadrature or QPSK ($M=4$), and 8ϕ PSK are described in Table 1.

The signal constellation is a pictorial representation of all possible signal states [1]. In each case, the transmitted

	BPSK	QPSK	8ϕ PSK
ENCODING EFFICIENCY	MAPS ONE BIT INTO ONE OF TWO SYMBOLS (1 bit/sym)	MAPS TWO CONSECUTIVE BITS INTO ONE OF FOUR SYMBOLS (2 bits/sym)	MAPS THREE CONSECUTIVE BITS INTO ONE OF EIGHT SYMBOLS (3 bits/sym)
$M = 2^N$	$2 = 2^1$	$4 = 2^2$	$8 = 2^3$
CODING EXAMPLE	<u>1 0 1 1 0 1</u>	<u>1 0 1 1 0 1</u>	<u>1 0 1 1 0 1</u>
	THIS SEQUENCE REQUIRES SIX SYMBOLS TO BE TRANSMITTED AT SYMBOL RATE = BIT RATE = R	THIS SEQUENCE REQUIRES THREE SYMBOLS TO BE TRANSMITTED. ALLOWS SYMBOL RATE $\frac{R}{2}$ WITH BIT RATE R OR SYMBOL RATE R WITH BIT RATE 2R	THIS SEQUENCE REQUIRES TWO SYMBOLS TO BE TRANSMITTED. ALLOWS SYMBOL RATE $\frac{R}{3}$ WITH BIT RATE R OR SYMBOL RATE R WITH BIT RATE 3R

Table 1. Three common versions of phase-shift keying (BPSK, QPSK and 8ϕ PSK).

signal is formed by appropriately weighting orthogonal carrier components. The weighting factor is such that the signals are constrained to lie on a circle of radius \sqrt{E} , where E is the transmitted signal energy. This constant-energy/constant-amplitude characteristic is important in satellite communication links where AM/PM conversion must be held to a minimum.

Again referring to Table 1, notice that QPSK and 8ϕ -PSK systems encode more bits of information per transmitted symbol than does BPSK. If a block of information must be transmitted over the same interval of time for all three cases, the signalling rate can be reduced in an M -ary system by a factor of N . And, since the maximum pulse rate (symbol rate) through a channel is proportional to its bandwidth, a reduced rate allows the use of narrower channels. Alternatively, if the symbol rate is held constant for all three cases, the higher-order systems transmit more bits of information through the fixed bandwidth channel. Therefore, M -ary systems are termed, *bandwidth efficient*. The price to be paid for efficiency, however, is an increase in the system probability of error, since decisions as to which symbol was transmitted at any given

time are now made in a more crowded signal space.

M -ary PSK may be characterized in the frequency domain by its spectral density, $G(f)$, which is of the form

$$G(f) = A^2 T_s \left[\frac{\text{Sin} \pi T_s (f - f_c)}{\pi T_s (f - f_c)} \right]^2 \quad [2]$$

where, $T_s = (\log_2 M) T_b$ the symbol period

$\frac{1}{T_b}$ = the bit rate

f_c = the carrier frequency

A^2 = a constant proportional to average power

BPSK and QPSK spectra are compared on an equal bit-rate basis in Figure 1. Note that in both cases the spectrum is continuous; i.e., there are no discrete spectral lines, and there are nulls at multiples of the symbol rate.

PSK Modulation Techniques

Although this article is concerned primarily with demodulation techniques involved in PSK systems, it will be helpful to also consider the encoding or modulation process. A typical BPSK modulator is shown in Figure 2.

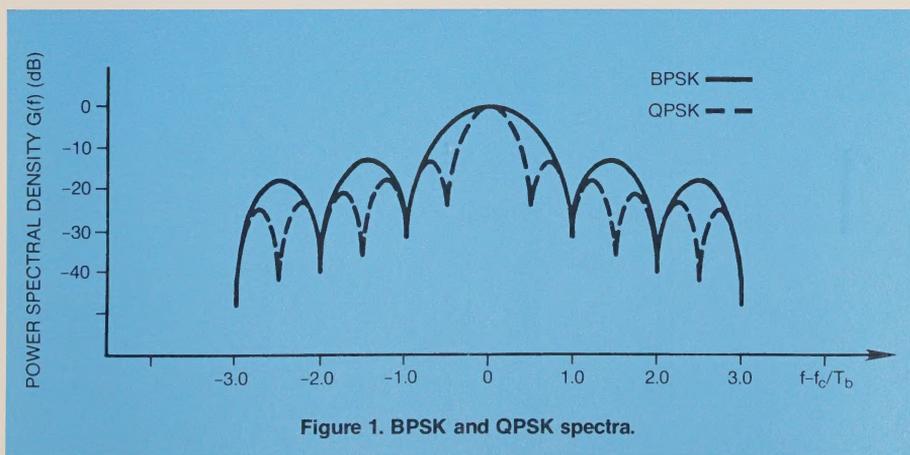


Figure 1. BPSK and QPSK spectra.

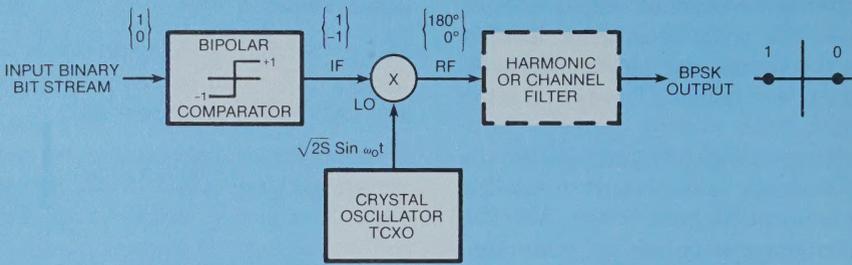


Figure 2. BPSK modulator.

The incoming unipolar waveform is converted to bipolar form, and switches current into and out of the IF port of a double-balanced mixer. Switching current in this fashion effectively imparts a 0° or 180° phase shift to the LO signal, $\sqrt{2S} \sin \omega_0 t$. At this point the waveform is ready for amplification and transmission, but sometimes is filtered to minimize intersymbol interference. This filtering will be discussed in a later section.

A block diagram for a QPSK modulator is shown in Figure 3.

PSK Demodulation

The demodulation process can be divided into three major subsections, as

shown by Figure 4. First, since the incoming waveform is suppressed carrier in nature, coherent detection is required. The methods by which a phase-coherent carrier is derived from the incoming signal are termed, *carrier recovery*, and will be covered first. Next, the raw data are obtained by coherent multiplication, and used to derive clock-synchronization information. The raw data are then passed through the channel filter, which shapes the pulse train so as to minimize intersymbol-interference distortion effects. (The channel filter is sometimes placed at the IF input of the demodulator with equivalent results.) This shaped pulse train is then routed, along with the derived clock, to the data sampler which outputs the demodulated data.

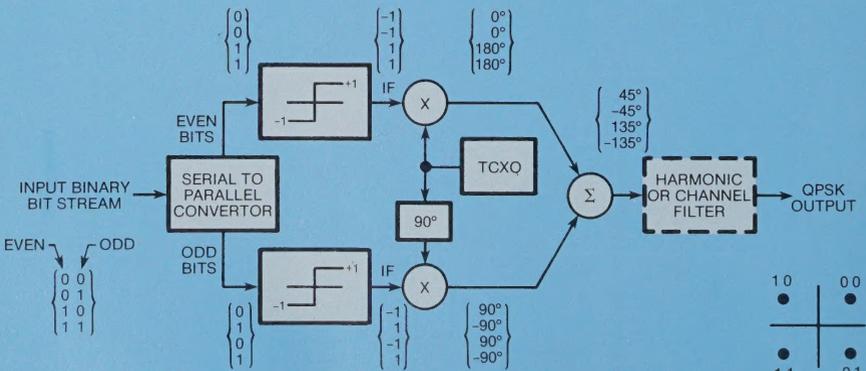


Figure 3. QPSK modulator.

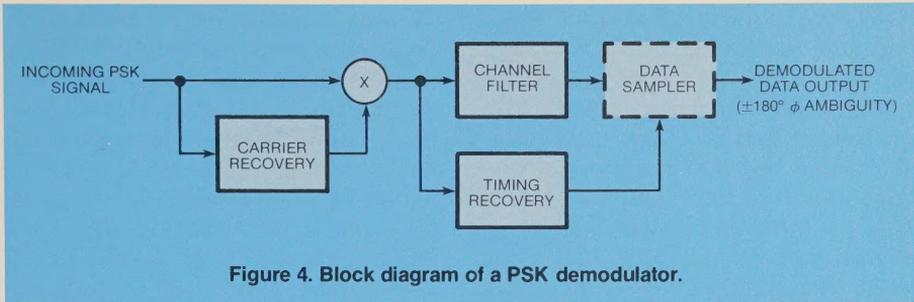


Figure 4. Block diagram of a PSK demodulator.

The demodulated data will still exhibit an Mth-order $\pm 180^\circ$ phase ambiguity which must be corrected. The most common correction scheme calls for the transmission of a known sequence as a data preamble. After preamble decoding, the demodulator then inverts the bit streams that are in error.

Carrier Recovery

The Costas Loop

The conventional Costas loop for BPSK suppressed carrier recovery is shown in Figure 5. Analysis of operation is lengthy and complex; the reader is referred to the many papers by Lindsey and Simon who developed much of the original work [3, 5, 6, 8]. In keeping with

their notation, the input signal can be expressed as

$$x(t) = \sqrt{2S} m(t) \sin \Phi(t) + n(t)$$

where, S = the average received signal power

$m(t)$ = the data modulation (± 1 bipolar digital waveform)

$\Phi(t) = \omega_0 t + \theta(t)$ the received signal phase

$n(t)$ = additive channel noise

$\hat{\Phi}(t) = \omega_0 t + \hat{\theta}(t)$ the VCO phase estimate

The Costas loop performs both phase-coherent suppressed carrier reconstruction and synchronous data detection within the loop. The upper loop is

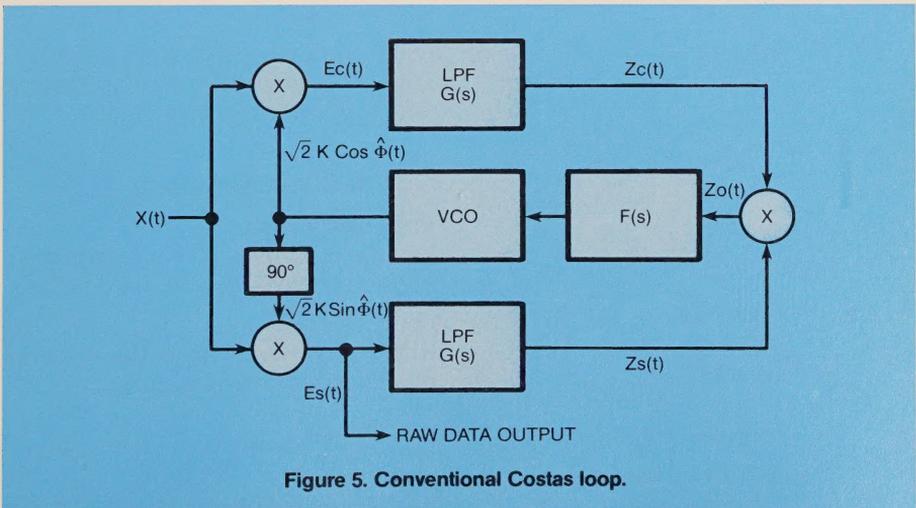


Figure 5. Conventional Costas loop.

referred to as the quadrature, or tracking loop, and functions as a typical PLL, providing a data-corrupted error signal, $Z_c(t)$. The lower in-phase, or decisioning loop provides data extraction at the output of the lower mixer, and corrects the data corruption of $Z_c(t)$. The corrected error signal, $Z_o(t)$, is applied through loop filter $F(s)$ to the VCO, which yields a phase estimate in the form $\text{Cos } \hat{\Phi}(t)$.

It can be shown that the Costas loop tracks a doubled phase error signal in the form

$$\epsilon(t) = Z_o(t) \alpha \text{Sin } 2\phi(t)$$

$$\text{with, } \phi(t) = \Phi(t) - \hat{\Phi}(t)$$

The variance of the doubled error tracking jitter $\sigma_{2\phi}^2$ is used for cycle-slipping calculations, while σ_ϕ^2 is used in bit error-rate calculations.

Much work has been done describing the *linear* PLL model, and for many carrier tracking analyses this model will suffice. Out of this work, a fundamental expression relates the mean-squared phase-error jitter to the SNR "in the loop."

$$\sigma_\phi^2 = 1/\rho \quad (\text{rads})^2 \quad \rho = S/N_o B_L \quad [4]$$

For a 2nd-order PLL with loop filter,

$$F(j\omega) = \frac{1 + j\omega \tau_2}{j\omega \tau_1}$$

$$\sigma_\phi^2 = \frac{N_o \omega_n}{A^2 4\zeta} (1 + 4\zeta^2)$$

$$= \left(\frac{S}{N_i}\right)^{-1} \frac{B_L}{B_i}$$

where, σ_ϕ = the rms phase jitter (rads)

$$\frac{S}{N_i} = \text{input SNR} \frac{A^2}{2N_o B_i}$$

B_L = one-sided loop bandwidth

B_i = double-sideband, one-sided IF bandwidth

This final expression is often used to determine loop bandwidths. Since carrier tracking can be optimized for a linear PLL by the adjustment of loop parameters, it is advantageous to analyze and specify the tracking performance of suppressed-carrier loops in the same way. Again, Lindsey and Simon have connected the two by an interesting relationship termed, *squaring loss* [5].

$$\sigma_{2\phi}^2 = 4/\rho S_L$$

$$\sigma_\phi^2 = S_L^{-1}/\rho$$

where, ρ = loop SNR $S/N_o B_L$

S_L = squaring loss

The term squaring loss (SL), is used to describe the degradation in loop SNR due to signal x noise and noise x noise distortion occurring in the arm filters. Dependent on the modulation format, input SNR, and filter type and bandwidth, the SL is quite difficult to calculate, even using simplifying expressions developed in [6]. Suffice it to say that as a practical matter, for uncoded systems, where $E/N_o > 10$ dB, there is little to be gained by implementing arm filters more complex than Butterworth 2 poles, which result in an SL of a couple of dB.

To put things into perspective, Table 2 catalogs some of the more important aspects of tracking performance.

Costas Loop Variations

The Polarity Loop

Figure 6 shows a very common implementation called the hard-limited, or polarity loop.

Ritter has shown that the optimal phase estimator requires a

$$\tanh\left(K \frac{E}{N_o}\right)$$

nonlinearity following the in-phase

$$\text{MEAN SQUARED PHASE JITTER} = \underbrace{\sigma_{\phi^2}^2 = \frac{1}{\rho}}_{\text{CARRIER TRACKING LOOP}} < \underbrace{\sigma_{\phi^2}^2 = \frac{1}{S_L \rho}}_{\text{SUPPRESSED CARRIER TRACKING LOOP}}$$

SL DEPENDENT ON:

- DATA FORMAT; e.g., NRZ, MANCHESTER, ETC.
- SYMBOL RATE
- INPUT SNR (E/N_0)
- ARM FILTER TYPE, ORDER, BANDWIDTH

INTERRELATIONSHIPS

LOOP BANDWIDTH \uparrow ACQUISITION TIME \downarrow PHASE JITTER \uparrow PROBABILITY OF ERROR $P(e)$ \uparrow

Table 2. Tracking performance.

data arm filter. For large values of its argument, $\tanh(x)$ equals the polarity or sign of x (± 1), and can be implemented with a hard limiter [7].

Simon has shown [8] that the inclusion of a limiter introduces a signal suppression factor into the analysis which can improve or degrade performance. Results indicate that for higher E/N_0 ratios, there is an actual improvement

in the loop's squaring loss. Also, inclusion of the limiter allows the substitution of a switching chopper multiplier for the analog (four quadrant) third multiplier, with its inherent dc-drift stability improvement.

A modified (hard-limited) Costas loop used for the demodulation of QPSK signals is shown in Figure 7. Not shown, is the required block that is

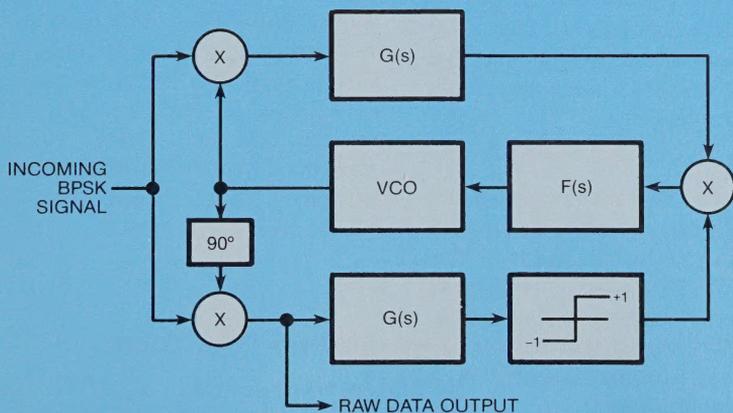


Figure 6. Hard-limited or polarity loop.

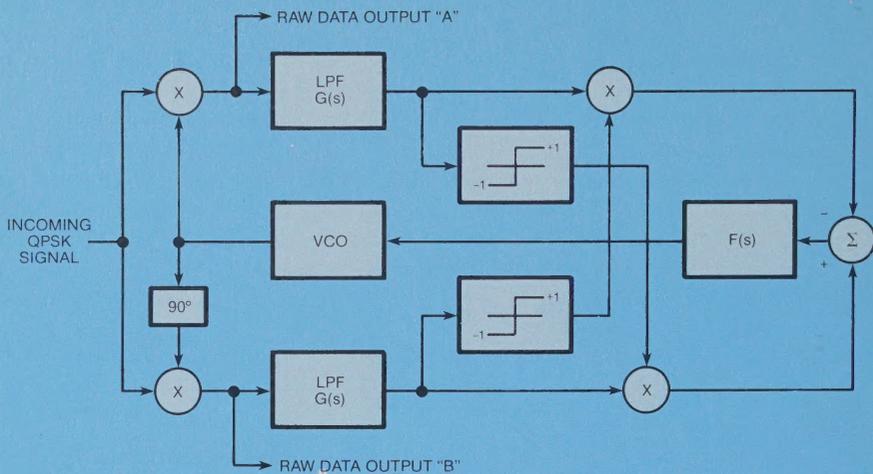


Figure 7. Modified (hard-limited) QPSK Costas loop.

used to interleave the two bit streams and resolve any $\pm 180^\circ$ phase ambiguities.

The Remodulator

Another popular carrier recovery technique is called remodulation, and a BPSK implementation is shown in Figure 8.

Again, as in the Costas loop, the remodulator generates a loop error signal proportional to the doubled phase error between incoming phase and its estimate; i.e.,

$$\epsilon(t) \propto \sin 2[\Phi(t) - \hat{\Phi}(t)]$$

It can be shown that the remodulator is stochastically equivalent to the polarity loop; i.e., hard-limited Costas loop. The remodulator, however, is typically implemented at frequencies lower than IF. This allows a digital (baseband) hardware realization, resulting in a low-cost demodulator.

A remodulation technique for QPSK carrier recovery and data extraction is

shown in Figure 9. This version of the QPSK remodulator loop can be shown to be stochastically equivalent to the modified QPSK Costas loop described earlier [8, 9]. Weber has developed an expression for the remodulator S curve, $g(\phi)$, the equivalent loop nonlinearity. For high SNR, the phase-detector error characteristic approaches a sawtooth with four stable lock points at 0° , 90° , 180° and 270° . This sawtooth ensures a rapid transition between lock points, minimizing the lingering hangup effect sometimes occurring in a conventional Costas loop, due to its $\sin \phi$ S-curve response. Therefore, the QPSK remodulator loop should exhibit a somewhat faster acquisition time when compared to a conventional QPSK Costas loop.

Multiply-Filter-Divide

Another method of QPSK carrier recovery used in high-rate, burst-mode systems is that of the multiply-filter-divide circuit shown in Figure 10.

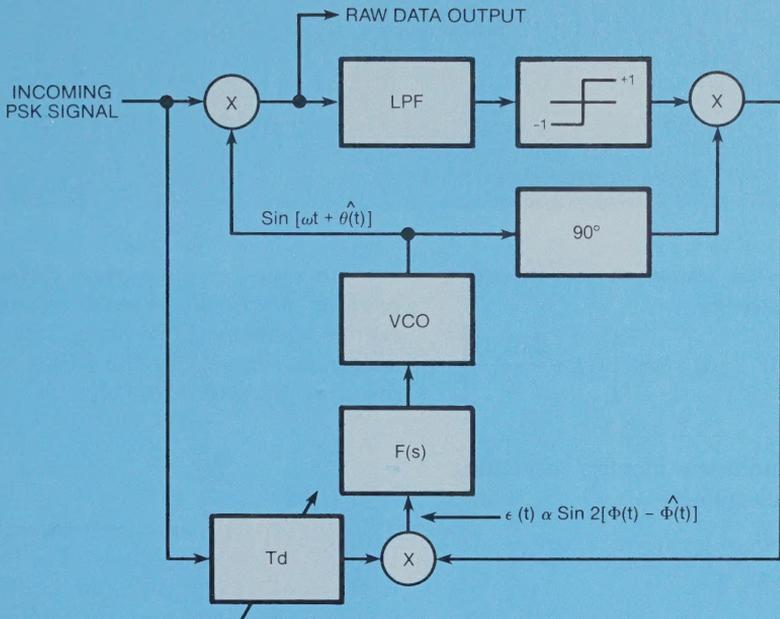


Figure 8. BPSK remodulator loop.

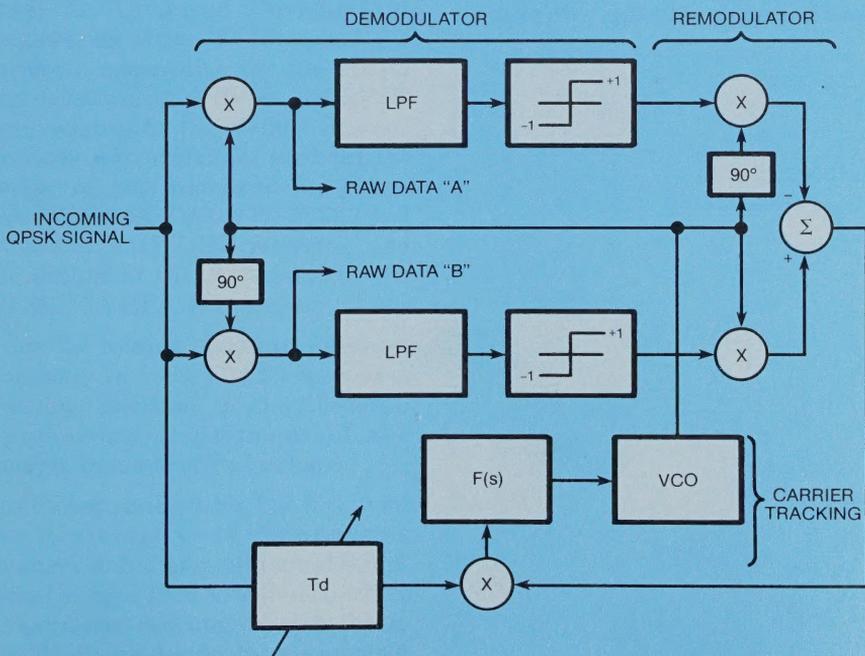


Figure 9. QPSK remodulator loop.



Figure 10. Multiply-filter-divide method of carrier recovery.

Consider the output of the 4th-order nonlinearity $y(t)$

$$y(t) = [x(t)]^4 \quad x(t) = \text{Sin} \left[\omega_0 t + \frac{2\pi(i-1)}{4} \right]$$

$$i = 1, 2, 3, 4$$

By trigonometric identity (assuming *ideal* quadrupling)

$$y(t) = \frac{3}{8} - \frac{1}{2} \text{Cos} [2 \omega_0 t + \pi(i-1)] +$$

$$\frac{1}{8} \text{Cos} [4 \omega_0 t + 2 \pi(i-1)]$$

The filtered output, $z(t)$, contains the desired harmonic at $f = 4f_{IF}$, with phase

zero (modulo 2π). Frequency division by four yields the desired coherent carrier component. Tracking jitter is determined largely by the BPF's suppression characteristics [10].

Conclusion

The second part of this article will cover the other two subsections of a PSK demodulator: the symbol timing-recovery circuitry and the channel filter. In addition, bit error rate (BER) performance will be discussed and a method of measurement will be suggested.

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