Frequency-Offset Insensitive Digital Modem Techniques

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ABSTRACT

Conventional DPSK systems are adversely affected by transmitter/receiver frequency offsets due to frequency reference errors and Doppler shifts. We present two DPSK modem concepts which avoid the long frequency acquisition process of conventional DPSK. One technique involves a modified demodulator for conventional DPSK signals, while the other involves making minor modifications to both the modulator and demodulator. Simulation results are provided showing performances relative to conventional DPSK.

INTRODUCTION

The desire for small low-gain antennas in mobile satellite systems results in power budgets permitting only relatively low data rates (e.g. 600 bps). Low data rates at the high carrier frequencies of satellite systems (e.g. 1.5 GHz) make DPSK demodulators very susceptible to frequency errors, which may be a significant fraction of the data rate. While in many applications the carrier can be frequency located and tracked with a phase-locked loop, for some applications, such as burst demodulation, the lock-on time is excessive.

We review first the "gold standard" – fully coherent demodulation. We then discuss conventional differential demodulation, which is often preferred because of the difficulty of establishing a sufficiently "clean" local phase reference with noisy input signals. For differential detection, we point out the important distinction between predetection and postdetection matched filtering (MF). It is shown that while predetection MF is required for optimum performance, postdetection MF can ease the frequency acquisition problem.

Two new modem techniques, both derived from DPSK, are suggested. The first utilizes conventional differential modulation and a new split delay line (SDL) technique to recover the signal, independent of carrier offset. The second (DDPSK) utilizes double differential modulation and then recovers data with a double differential demodulator using either pre- or postdetection MF.

These techniques are examined for the case of binary phase shift keying (BPSK) using a square symbol shape. This case is important in satellite applications, which tend to be power limited rather than bandwidth limited.

Conventional Binary Modem Techniques

Phase shift keyed (PSK) modulation and coherent demodulation constitute the most power efficient data transmission technique. In BPSK modulation, the transmitted carrier is shifted in phase by 0 or π radians, depending on the transmitted data. Demodulation is accomplished at the receiver by multiplication with a regenerated, phase-locked carrier followed by baseband MF. For square modulation, the MF is an integrate and dump device. Figure 1 shows a block diagram of a BPSK demodulator.

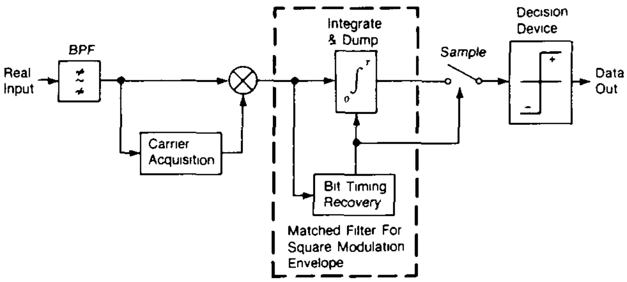

Fig. 1. Coherent BPSK demodulator

The bit error rate (BER) for BPSK in additive white gaussian noise (AWGN), using ideal coherent detection, is given by

$$BER_{BPSK} = 0.5erfc(E_b/N_0) \quad (1)$$

Coherent demodulation requires *three* levels of parameter acquisition — carrier frequency, carrier phase and data clock. DPSK modems require only carrier frequency and data clock acquisition.

In DPSK modulation, the reference phase for any transmitted symbol is the previous symbol. Demodulation may be accomplished by differential detection, which is correlation detection using the previous symbol as the reference. A choice exists in DPSK of performing MF before or after differential detection. Predetection MF is superior because detection is a nonlinear process. As a result filtering after detection always yields greater noise power than filtering before detection. Figure 2 shows the block diagram of optimum DPSK, using predetection MF. Postdetection MF would involve moving the integrate and dump device to immediately after the detector. In the latter case, the noise bandwidth at the detector input would be established by the IF filter.

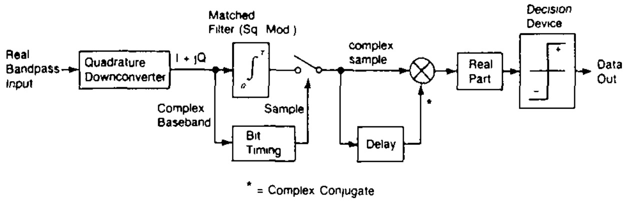

Fig. 2. Optimum DPSK demodulator (predetection MF)

The bit error rate (BER) for optimum DPSK is given by:

$$BER_{DPSK} = 0.5exp(-E_b/N_0) \quad (2)$$

The analytical expression for the BER of DPSK using postdetection MF has not been derived and does not appear to be available in the open literature. However, simulation results showing the degradation incurred by postdetection MF are presented in Figures 5, 7 for a IF-bandwidth/data-rate ratio of 8.

As mentioned above, DPSK does require carrier frequency acquisition. In land mobile applications, the Doppler shift due to vehicle motion can be of the order of 100 Hz, while typical data rates are 600-1200 bps. Thus, even without transmitter/receiver frequency drift, Doppler shift can be a significant source of frequency error.

Both pre- and postdetection MF DPSK suffer performance degradations due to frequency offset. However, the susceptibilities are different. In the case of postdetection MF, with a relatively wide IF bandwidth, the error will only be due to the carrier phase error, $\Delta\omega.\tau$, where $\Delta\omega$: frequency offset in radians and τ: symbol period. On the contrary, predetection MF suffers both due to the carrier phase error as well as a reduction in the MF's peak output amplitude. The latter is referred to as correlation loss and has a sin $(\Delta\omega.\tau/2)/(\Delta\omega.\tau/2)$ dependence on $\Delta\omega$.[1] It is clear that, for frequency offsets less than 25% of the data rate, the correlation loss is a much weaker function of $\Delta\omega$ than the carrier phase error. Therefore, the degradations of pre- and postdetection MF DPSK are similar for small frequency offsets, but predetection MF suffers greater degradation for large offsets.

NEW MODEM PROPOSALS

Basic Concept

We now present two modifications of conventional DPSK that considerably reduce the sensitivity to frequency offsets. Both techniques use a common overall demodulation philosophy – *double differential detection* – although they were developed independently. The basic concept of double differential detection is that a time-invariant carrier phase error, as defined above, may be cancelled by two cascaded differential detections involving three equidistant points in time. One application of the above concept is termed the Split Delay Line (SDL) demodulator, and applies double differential detection to a conventional DPSK waveform; hence it can be retrofitted to existing DPSK transmission systems. The other technique, Double Differential Phase Shift Keying (DDPSK), involves modifications to both the modulator and the demodulator of conventional DPSK. The advantage of DDPSK over SDL is greater power efficiency, although both techniques are less efficient than DPSK in the absence of frequency offsets. Both SDL and DDPSK can be used with pre- and postdetection MF. The details of the two techniques are given below.

Split Delay Line Demodulation

The following discussion of postdetection MF DPSK and SDL DPSK utilizes the arc tangent and manipulates only the angle. Both approaches are shown in Figure 3.

The input signal is:

$z(t) = x(t) + jy(t)$, where
$x(t) = \cos(\omega t + \phi(t))$;
$y(t) = \sin(\omega t + \phi(t))$;
$\phi(t) = 0, \pi$; and
τ = the bit period.

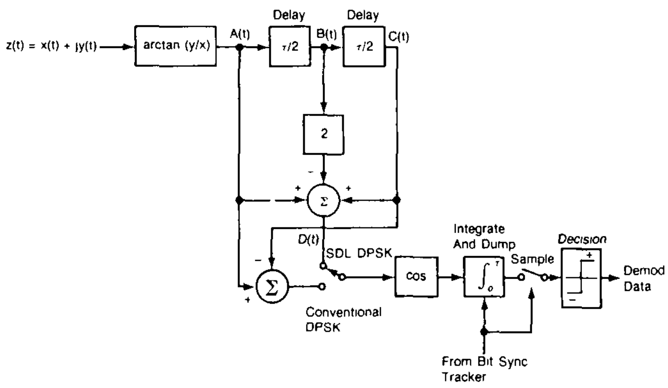

Fig. 3. DPSK and split delay line demodulator (postdetection MF)

In DPSK, we extract the angle using the arc tangent function and, using a single delay line of length τ, form the difference:

$$[\omega t + \phi(t)] - [\omega(t - \tau) + \phi(t - \tau)]$$
$$= \phi(t) - \phi(t - \tau) + \omega\tau$$

We then require that the original modulator choose $\omega\tau = 2\pi n$, where n is an integer. Then

$$\cos[\phi(t) - \phi(t - \tau) + \omega\tau] = \pm 1,$$

which is the desired signal. However, as $\omega\tau$ approaches 90 degrees, the useful output is reduced to zero.

In satellite systems we do not have sufficient control of ω, as received with Doppler shift and tuning errors, to guarantee that $\omega\tau$ will be close to $2\pi n$. This results in a carrier phase error, which is overcome in the SDL approach as shown in Figure 3, which instead forms:

$$\begin{aligned} D(t) = \cos[&\omega t+\phi(t) \\ &- 2[\omega(t-\tau/2) + \phi(t-\tau/2)] \\ &+ \omega(t-\tau) + \phi(t-\tau)] \\ = \cos&[\phi(t) - 2\phi(t-\tau/2) + \phi(t-\tau)] \quad (3) \\ = \pm 1&\text{, the desired signal.} \end{aligned}$$

To show the last step, we observe that the argument of the cosine is $[\phi(t) - \phi(t-\tau)]$ during the first half of the symbol and $-[\phi(t) - \phi(t-\tau)]$ over latter half. Since the cosine is the same in both cases, we obtain the desired signal.

For both DPSK and SDL, the cosine output is passed through an integrate and dump MF (for square envelope) that performs integration over the full symbol. Adequate symbol synchronization is assumed. The output of the MF is sampled for bit decisions at the end of the integration period.

Predetection MF for SDL is similar to that for DPSK (c.f. Figure 2) with the exception that four half-symbol predetection integrations (#1, 2, 3 and 4) are performed over two adjacent symbols. Then, SDL processing (equation (3)) is performed using MF outputs (#1, 2, 3) or (#2, 3, 4). Approximately 1-dB of additional performance improvment may be realized by equal-gain combining the two SDL outputs; this was implemented in the simulation model for predetection MF SDL.

The SDL receive processing expressed by equation (3) is equivalent to two cascaded levels of differential detection involving signals A(t), B(t) and C(t) in Figure 3. The first involves A(t),B(t) and B(t),C(t) , while the second differential detection involves the outputs of the first.

Double Differential Phase Shift Keying

In DDPSK, the data is encoded not on the *first* difference of the phase between *two* adjacent symbols (as in DPSK), but on the *second* difference of the phase involving *three* adjacent symbols. This concept is illustrated in Table 1. It is noteworthy that the rows for BPSK, DPSK 1st Difference, and DDPSK 2nd Difference contain identical entries. This implies identical data outputs from the respective demodulators.

Table 1. BPSK, DPSK and DDPSK modulation/demodulation

DATA IN		1	0	1	1	0	0	0	1
BPSK		π	0	π	π	0	0	0	π
DPSK	ϕ	$\phi+\pi$	$\phi+\pi$	ϕ	$\phi+\pi$	$\phi+\pi$	$\phi+\pi$	$\phi+\pi$	ϕ
1st Dif		π	0	π	π	0	0	0	π
DDPSK ϕ	ϕ	$\phi+\pi$	ϕ	ϕ	$\phi+\pi$	ϕ	$\phi+\pi$	ϕ	ϕ
1st Dif	0	π	π	0	π	π	π	π	0
2nd Dif		π	0	π	π	0	0	0	π

Figure 4 shows a block diagram of the DDPSK demodulator using postdetection MF. Note that the MF follows the *first* differential detector. The input to the second differential detector is a complex sample at the symbol rate. Hence, the additional computation load over DPSK demodulation is minimal.

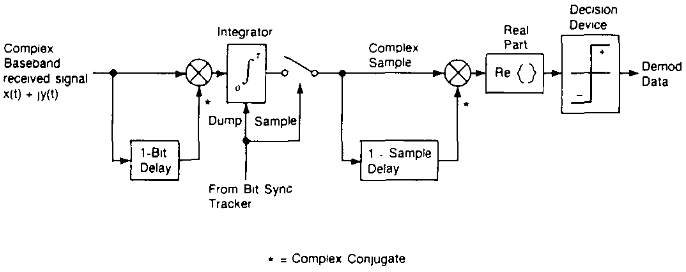

Fig. 4. Double differential PSK (DDPSK) demodulator (postdetection MF)

To implement the predetection MF version of DDPSK demodulation, one simply moves the integrate and dump device to a position prior to the first differential detector. The input to the first differential detector is then a complex sample at the symbol rate. Although accurate frequency acquisition is not required in DDPSK, symbol synchronization *is* required, as in any other data modem. DDPSK symbol synchronization is no more difficult than that of DPSK. Hence, similar techniques may be used.

MONTE CARLO SIMULATIONS

Monte Carlo, discrete time simulations were performed to examine the BER performances of the SDL and DDPSK modems relative to conventional DPSK. Results were obtained with both pre- and postdetection MF, and both with and without frequency offset.

Results

The results are shown in Figures 5-8. The following abbreviations are used for the different modem curves:

A: Theoretical coherent BPSK (no frequency offset).
B: Theoretical DPSK (no frequency offset).
C: Simulated DPSK (frequency offset as specified)
D: DDPSK (frequency offset as specified)
E: SDL (frequency offset as specified)

The curves A and B are shown in each figure for reference.

In Figure 5, the simulation results for DPSK are very close to the theoretical values, which provides a measure of assurance for the validity of the simulation model. Using BER=10^{-3} as the reference, we note that, in the absence of frequency offset, DDPSK is approximately 3.5 dB and SDL 6 dB worse than DPSK. Figure 6 shows that, in the presence of 100-Hz frequency offset (which is 20% of the data rate) the performance of DPSK suffers extreme degradation, whereas the degradations are 0.5 dB for DDPSK and immeasureably small (at these E_b/N_0 values) for SDL. At BER=10^{-3}, the power efficiency of DPSK equals that of DDPSK at a frequency offset of approximately 57 Hz, while it is equal to that of SDL at 72-Hz offset.

The predetection MF results may be explained as follows. For DPSK, the major source of degradation at 20% of the data rate is the carrier phase error, while the contribution of correlation loss is relatively quite small. The SDL and DDPSK modems suffer a small degradation because they are insensitive to the carrier phase error but, for the given offset value, *are* mildly sensitive to the correlation loss.

The major observations from the results for postdetection MF (Figures 7, 8) are as follows. In the absence of frequency offset, the degradation due to postdetection MF (relative to predetection MF) is 2.2 dB for DPSK, 0.7 dB for DDPSK and 2 dB for SDL. The 100-Hz frequency offset produces severe degradation in the case of DPSK. However, there is *no degradation* for DDPSK and SDL. The absolute frequency insensitivity of SDL and DDPSK in the postdetection MF case is due to the absence of prefiltering of the input signals (in the simulation), resulting in zero correlation loss. In practice, some prefiltering will always exist due to the bandpass IF stage, which is necessary to limit the noise power.

It should be noted that the quantitative results presented here for postdetection integration are valid only for the specific ratio of the input noise bandwidth (4 kHz) to the noise bandwidth of the postdetection integrator (500 Hz). A greater ratio between the two will yield greater degradation of postdetection MF relative to predetection MF.

CONCLUSIONS

Two new modem proposals are presented in this paper — DDPSK and SDL. Both are derivatives of binary DPSK but do not share its performance sensitivity to frequency offsets. Both techniques are less power efficient than DPSK in the absence of frequency offsets. However, in the presence of frequency offsets greater than 12% of the data rate, DPSK is worse than DDPSK, while at 15% offset, the efficiency falls below that of SDL.

Both DDPSK and SDL can be used with either pre- or postdetection MF. DDPSK is fairly insensitive to the type of MF. This means that DDPSK can be operated with a wide IF bandwidth (e.g. 4-kHz for a 500-baud data signal), with no post-IF frequency acquisition. SDL offers similar frequency insensitivity to DDPSK but is less power efficient.

REFERENCES

1. **Henry, J. C. III.** Dec. 1970. DPSK Versus FSK with Frequency Uncertainty. *IEEE Trans. Comm. Systems*, pp. 814-816.

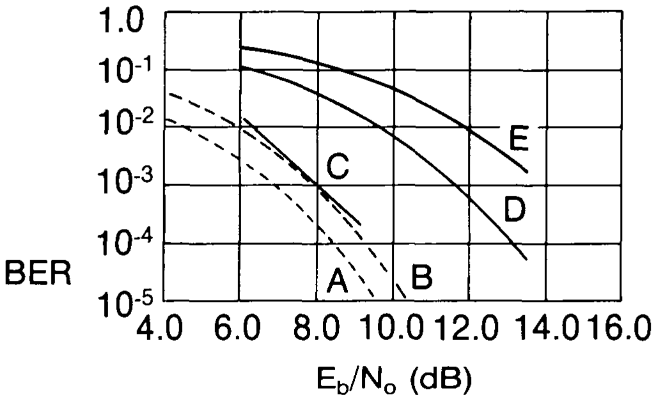

Fig. 5. Predetection matched filtering (no frequency offset)

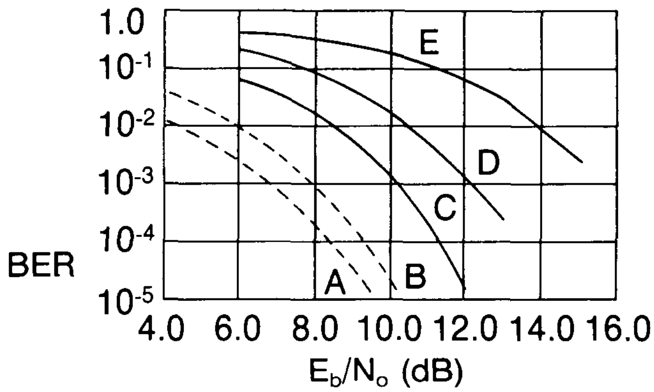

Fig. 7. Postdetection matched filtering (no frequency offset)

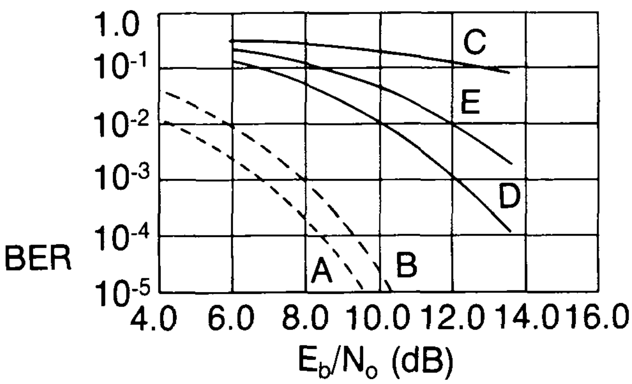

Fig. 6. Predetection matched filtering (100-Hz frequency offset)

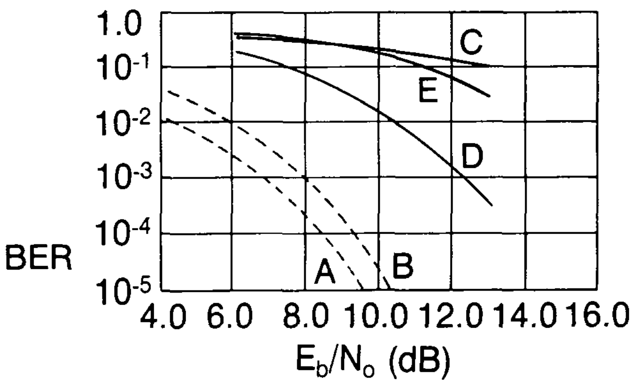

Fig. 8. Postdetection matched filtering (100-Hz frequency offset)