A POWER-EFFICIENT BPSK COMMUNICATIONS SYSTEM FOR SMALL SATELLITES

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This work was supported as a joint effort between Cynetics Corporation, the South Dakota School of Mines and Technology, and the South Dakota Governor's Office of Economic Development, through the South Dakota Futures Fund Program.

ABSTRACT

Many of the small satellites which have been launched or designed to date have used Frequency Shift Keyed (FSK) modulation for the communications link. FSK necessarily suffers a best-case signal-to-noise ratio (SNR) loss of 3 dB for coherent demodulation. Many, if not most, of the FSK systems in use today employ non-coherent demodulation which suffers additional SNR loss. This means that small satellites using FSK must use two or more times the minimum power required for the communications link. A small satellite using two watts for an FSK communications link could save at least 1 watt by using Bi-Phase Shift Keying (BPSK) or one of the other power-optimal modulations. This saved power would then be available for payloads or for increased data communications. Alternately, a satellite with one-half the solar-cell surface area could be used.

Cynetics Corporation has tested a commercially available 9.6 Kb/sec communications system which uses asynchronously detected, non-coherent FSK. This system has a measured implementation loss of 23.6 dB, which is roughly 20 dB worse than the 3 dB implementation loss one might expect. When the additional 3 dB FSK loss is considered, this system was 23 dB worse than a simple BPSK system with a 3 dB implementation loss. This means that this FSK system would require two hundred times (23 dB) as much satellite transmitter power as a reasonable BPSK system.

Cynetics is completing the development of a 9.6 Kb/sec (BPSK) satellite communications link using synchronous matched-filter data detection. BPSK is one of the optimal pulse modulation methods (in an SNR and power-efficiency sense) which can save substantial power in a satellite transmitter. Cynetics' BPSK system modulates and demodulates at the standard satellite communications IF frequency of 70 MHz. The expected performance is a 10^{-6} bit error rate for -116 dBm (2.5×10^{-15} watts) received signal power at the input to a 0.5 dB noise figure low-noise amplifier.

INTRODUCTION

Bi-Phase Shift Keying (BPSK) modulation is more power-efficient than Frequency-Shift Keying (FSK) modulation. Since it has an inherent 3 decibel (dB) detection advantage over coherent FSK, coherent BPSK requires the transmitter to use only one-half the power that coherent FSK requires to obtain the same level of performance. Non-coherently detected FSK suffers an even greater performance degradation, and the advantages of BPSK are even greater. This is a particularly important savings for small-satellite communications systems, where the total power available is limited by the ability of the satellite to collect solar energy to run the communications system. For example, if a small satellite is able to collect enough solar energy to run a coherent FSK communications system, then the same satellite using BPSK would be able to communicate twice as much data to the ground. Alternately, the power savings could be used for greater payload power. This power savings in the communications system would make many additional satellite uses practical.

Cynetics has designed and constructed a brassboard 9.6 Kilobit-per-second (kbps) BPSK satellite communications modem using the standard 70 MHz intermediate frequency (IF). After a period of collecting user feedback, this modem will be made available to the small-satellite community.

This paper will compare the bit-error rate performance of several modulation types, showing the advantages of using a coherently-detected, antipodal modulation, such as BPSK. The Cynetics BPSK modem brassboard will then be described.

COMPARISON OF MODULATION TYPES

A trade-off exists between the receiver simplicity of an easily-demodulated signal type and the efficiencies of that signal. Two of the efficiencies of major concern in satellite communications systems are the spectral efficiency and the power efficiency.

Spectral Efficiency

Spectral efficiency refers to the ratio of the data rate to the bandwidth of the signal. This ratio then expresses the data rate per Hertz of bandwidth, and it is expressed in bps/Hz. Nyquist's Minimum Bandwidth Theorem shows that it is possible to transmit 2 bps/Hz at baseband without coding [1]. Multiple-level hybrid phase-amplitude systems or M-ary systems are able to achieve higher spectral efficiencies at the cost of greater complexity.

However, it still must be borne in mind that the maximum error-free data rate of these systems is ultimately limited by the signal-to-noise ratio (SNR), as expressed in Shannon's Channel Capacity Theorem.

Power Efficiency

Power-efficiency refers to the ratio of the data rate to the power required to transmit the data error-free. Since in an actual system, the power required also depends on noise figures, antenna gains, the distance separating the transmitter and receiver, etc., relative comparisons must be made. One simple method of doing this is to compare the SNR's required for the same bit-error rate (BER). Then, systems which are identical in noise figure, path loss, etc., but different in modulation, can be compared. The difference in required SNR indicates the relative performance of the modulation.

Efficiencies for Several Modulations

Table 1, after [2], shows the maximum baseband spectral efficiency of several modulation types. To obtain this maximum spectral efficiency, special filtering may be required. For example, the spectral efficiency of the main-lobe of the sin(x)/x spectrum of a BPSK signal is 1 bps/Hz, but this spectrum can be filtered further, without loss of data, provided that appropriate complimentary filters are used in the receiver. Although this additional filtering "smears" the transmitted data bit into the adjacent bit, the received, smeared bit can be forced to have a zero-crossing at the decision sampling instant. When this is done, there is no inter-symbol interference (ISI) at the sampling instant, and consequently the bandwidth can be decreased without a loss in performance. (The gain in the transmitter would have to be increased to compensate for the filter loss, so that the transmitted energy per bit would remain the same. For more information, refer to Nyquist's "ISI and Jitter-Free Transmission Theorem ." This may be found in many communications references, such as [1].) Note that Table 1 shows that FSK and BPSK have equal spectral efficiencies.

Table 1. Signal Speed of Representative Modulation Methods

Modulation Method	Maximum Speed, (bps/Hz)	Corresponding E_b/N_o dB for 10^{-4} BER
	Amplitude-shift keying	
OOK - coherent detection	0.8	12.5
	Frequency-shift keying	
FSK - coherent detection (d = 1)	0.8 (discriminator detection)	
FSK - noncoherent detection (d = 1)	0.8	11.8
CP-FSK - noncoherent detection (d = 0.7)	1.0	10.7
MSK (d = 0.5)	1.9	9.4
MSK - differential encoding (d = 0.5)	1.9	10.4
	Phase-shift keying	
BPSK - coherent detection	0.8	9.4
DE-BPSK	0.8	9.9
DPSK	0.8	10.6
QPSK	1.9	9.9
DQPSK	1.8	11.8
8-ary PSK - coherent detection	2.6	12.8
16-ary PSK - coherent detection	2.9	17.2
	QAM	
16-ary QAM	3.1	13.4

Table Two (also after [2]) shows the maximum power efficiency of several modulation schemes. The energy-per-bit (E_b) to noise power spectral density (N_o) signal-to-noise ratios in the table are for a BER of 10^{-4}. The power efficiency of <u>coherent</u> FSK is 3 dB worse than coherent BPSK. The additional degradation for non-coherently detecting FSK is 1.1 dB. So, at a BER of 10^{-4}, non-coherent FSK suffers a 4.1 dB degradation over BPSK. This degradation means that a 2.57 watt transmitter for non-coherent FSK could be replaced with a 1.0 watt bpsk transmitter with no degradation in performance.

Note that Table 2 indicates that continuous-phase FSK (CP-FSK) can achieve a higher spectral efficiency than BPSK if the observation interval is over three bits in order to make a one bit decision. This same process can be performed on the BPSK signal, with a corresponding increase in power efficiency. Note also that quadra-phase shift-keying (QPSK) and offset-keyed QPSK (OK-QPSK) have the same spectral efficiency as BPSK. Since QPSK uses sine and cosine channels, which are orthogonal (independent), then QPSK can be considered as the superposition of two independent BPSK channels, giving the same power efficiency.

Table 2. Ideal Power Efficiency of Representative Modulation Methods

Modulation method	E_b/N_o, dB for 10^{-4} BER
Amplitude-shift keying	
OOK - coherent detection	11.4
OOk - envelope detection	11.9
Frequency-shift keying	
FSK - noncoherent detection (d = 1)	12.5
CP-FSK - coherent detection (d = 0.7)	7.4*
CP-FSK - noncoherent detection (d = 0.7)	9.2*
MSK (d = 0.5)	8.4
MSK - differential encoding (d = 0.5)	9.4
Phase-shift keying	
BPSK coherent detection	8.4
DE-BPSK	8.9
DPSK	9.3
QPSK	8.4
DQPSK	10.7
OK-QPSK	8.4
8-ary PSK coherent detection	11.8
16-ary PSK coherent detection	16.2
QAM	
16-ary QAM	12.4

* For a three-bit observation interval.

The difference in power efficiency between BPSK and coherent FSK can be readily explained in the following fashion: In FSK, a data 1 causes frequency f_1 to be transmitted. A data 0 causes f_0 to be transmitted. The optimum detection scheme for the FSK signal is to filter about f_1 and coherently demodulate the f_1 signal, while simultaneously performing the same operation about f_0. Each of these "channels" then appears to have an on-off keyed (OOK) signal in it: about f_1, the carrier is present when the data is a 1, and absent when the data is a zero. The opposite is true for f_0. The FSK signal can then be viewed as the superposition of two noise-independent OOK channels, with the same performance as OOK. (This identical performance between coherent FSK and coherent OOK is indicated in Table 2.) However, it is true that the f_0 "channel" can be used as a threshold reference for "channel" f_1, so that the SNR-variable threshold of OOK is not required. Alternately, the degradation (over BPSK) of coherent FSK detection can be understood by noting that when "channel" f_1 is compared to "channel" f_0, the noise in the two channels will be statistically independent. (This is for a sufficiently wide separation of the two frequencies. When the frequency separation is decreased in the proper manner, an MSK signal, with its improved performance, is obtained.) Since the 1/0 decision is made by comparing the measurement of energy in "channel" f_1 with the energy in "channel" f_0, this comparison sees twice the noise energy, or twice the equivalent noise power. Consequently, the signal power must be doubled to obtain the same post-detection SNR. Hence, coherent FSK requires an additional 3 dB (a factor of two) in signal power over BPSK.

BER Performance for BPSK and FSK

Figure 1 shows the BER as a function of SNR for the ideal case for BPSK, coherent FSK, and non-coherent FSK. The 3 dB degradation of FSK over BPSK is evident, as is the additional degradation of non-coherent FSK over coherent FSK.

Choice of a Modulation for Small Satellites

Since small, solar-powered satellites are necessarily power-limited, a power-efficient modulation scheme should be employed. This is not to say that there will not be applications where a requirement for receiver simplicity may mandate the use of power-inefficient modulations. For example, a low data-rate satellite may be required to transmit to a large number of receivers. An FSK implementation may decrease the receiver cost sufficiently to overcome the 3 dB FSK disadvantage. However, the 3 dB advantage of BPSK could still be applied to doubling the data capacity of the same satellite, resulting in a potential doubling of revenue from the satellite. Also, the cost advantages of using a specific modulation type over another may decrease with the number of receivers. It is also true that economic concerns alone will not drive this decision, but also regulatory restrictions on bandwidth; the ease or difficulty of obtaining frequency allocations; limits on radiated power; etc.

At the present time, small satellites appear to be considered more as busses than purely as communications relays. The data rates have been low (relative to large geosynchronous satellites), and the number of receivers envisioned for each satellite has also been relatively low, especially for satellites with metrological or experimental payload packages. BPSK modulation is a good choice for these small satellites for the following reasons:

1. The very-limited satellite power is conserved. This allows more power for payload usage, or for increased communications. Consequently, many additional opportunities for small satellites can be pursued.

2. BPSK is one of the simplest power-efficient modulations. It is well understood, gives very good performance in practice, and the necessary components are readily available.

3. Spectral efficiency is not as critical for low data rates. Since the maximum data rate of any small satellite is limited by the power available for the communications system, the average data rates for small satellites are necessarily low. Since large bandwidths are not required for low data rates, it is expected that the required narrow-band frequency allocations will be available without the requirement for absolute-minimum bandwidth. It should be recognized, however, that as spectral crowding increases, spectrally efficient modulations, with their increased cost and complexity, will be required more often.

4. BPSK provides an upward path to higher-order modulations with increased spectral density. As stated earlier, QPSK can be viewed as the superposition of two independent BPSK channels, so that an eventual upgrade to QPSK can be achieved without complete re-training of technical staff. Many of the even-more spectrally efficient modulations also use phase-modulation, so upgrading from BPSK to these is potentially easier than a complete change in the underlying modulation formats. M-ary phase-shift keying (PSK) modulations, such as 8-PSK or 16-PSK, can be considered as combinations of BPSK signals, although the combinations are no longer orthogonal as they are with QPSK. Quadrature-amplitude modulation (QAM) also uses PSK -- with a combination of amplitude-shift keying (ASK). QAM is one of the most spectrally efficient modulations in use. The phase-modulation skills obtained in using BPSK modulation would still be applicable to

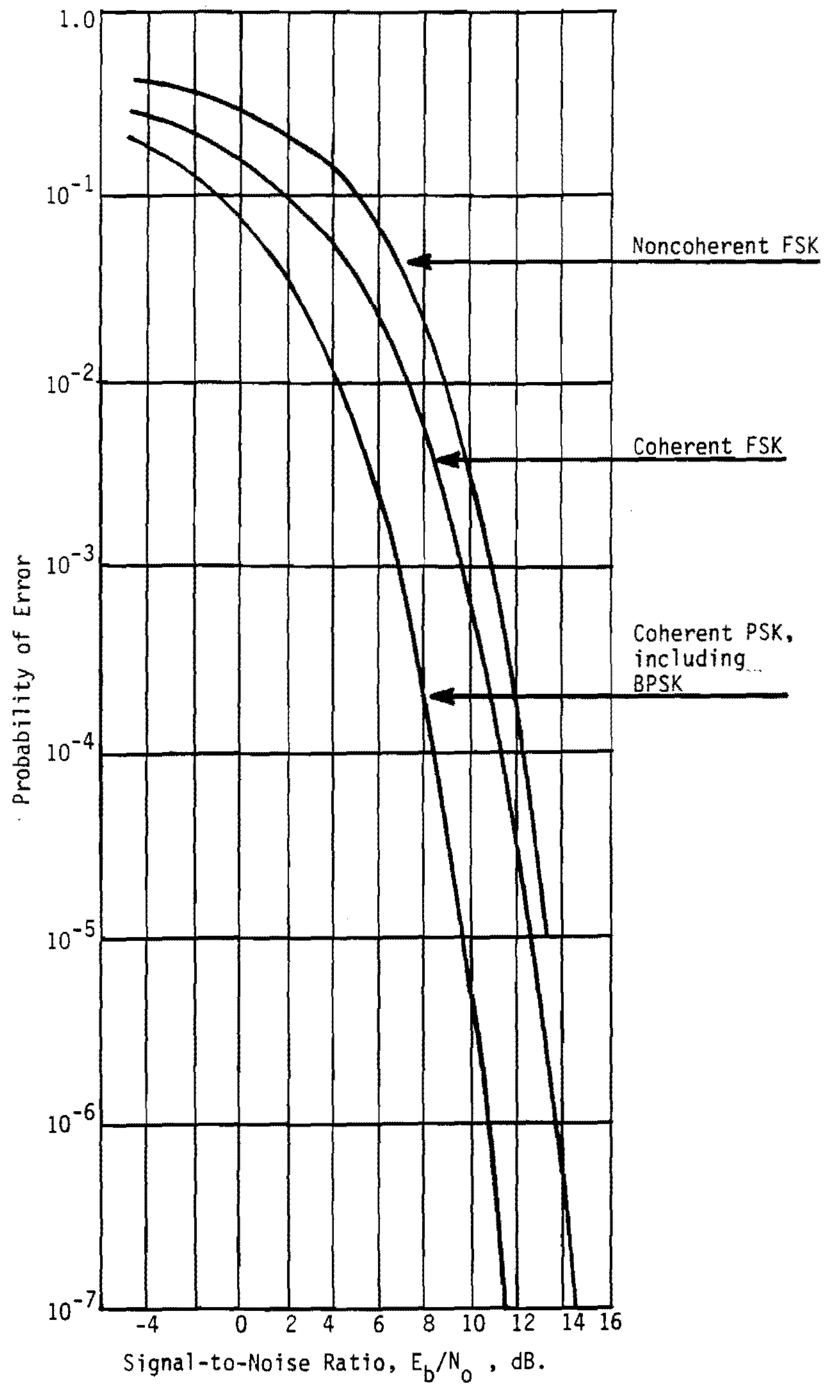

Figure 1. BER performance of BPSK, coherent FSK, and noncoherent FSK.

QAM, so that re-training costs would be less than the re-training costs in upgrading from non-PSK modulations to QAM.

BPSK is therefore a good modulation choice for many small-satellite communication systems. Other modulations are more spectrally efficient or require somewhat simpler receivers, but BPSK achieves the optimum power efficiency for single-observations per bit. Minimum-shift keying (MSK) is able to obtain the same power-efficiency; it has increased spectral efficiency (see Table 1); and good implementations of MSK could also be relatively simple. However, MSK does not provide a good path for upgrading to higher-order modulations, and it is not as commonly used as the PSK's.

MODEM DESCRIPTION

The brassboard satellite modulator-demodulator (modem) that Cynetics has designed and constructed uses BPSK without minimum-bandwidth filtering, since the relatively low data rates for small satellites are not expected to require absolute-minimum bandwidths, as discussed previously. Also, the additional complexity of using phase equalizers for reducing inter-symbol interference (ISI) in the demodulator was avoided by using Bessel filters. Bessel filters have less group delay distortion, and consequently lower ISI than Butterworth or Chebyshev filters. Bessel filters do not roll off as fast, but again, this was considered acceptable due to the narrow data bandwidth. Without phase-equalization, there is some residual ISI, but as with many BPSK systems, the residual ISI was considered more acceptable than the added complexity of equalization.

Figure 2 is a photograph of the complete modem system. Note the modular construction of the modem, which allows simplified testing. Figure 3 shows the connections for the modem. Figure 4 shows the interiors of the modem modules.

Subsystem Module Functions

Modulator. Figure 5 is the Functional Block Diagram of the modem system. The Modulator is the transmitting portion of the modem. In the Modulator, the data to be transmitted is differentially encoded to resolve the 0° / 180° phase ambiguity. The baseband data is then filtered for the main spectral lobe using a third-order Bessel low-pass filter. This filtered-and-encoded data then modulates the carrier provided by the 70 MHz oscillator.

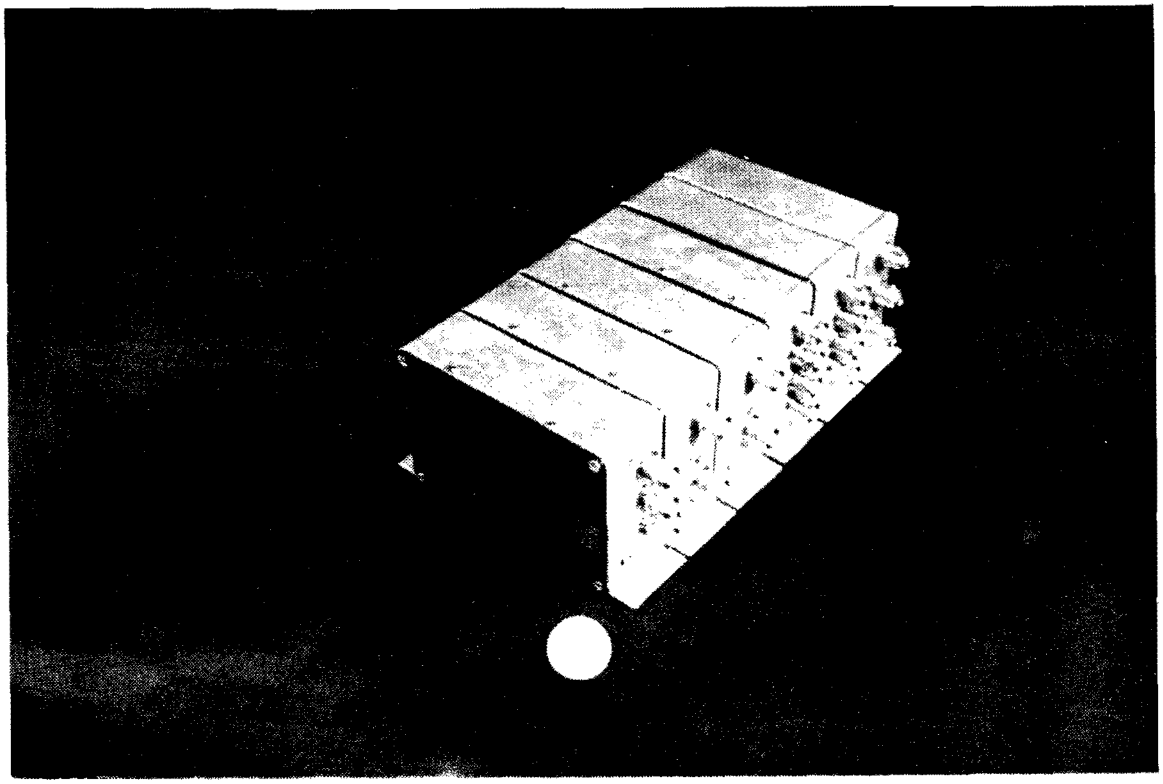

Figure 2. The BPSK Satellite Communications Modem.

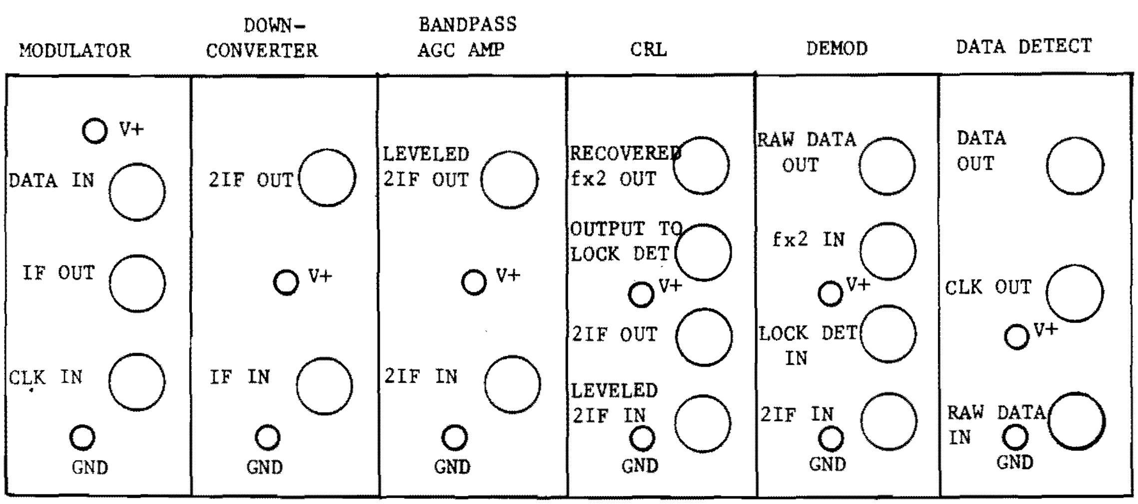

Figure 3. The Modem Interconnections.

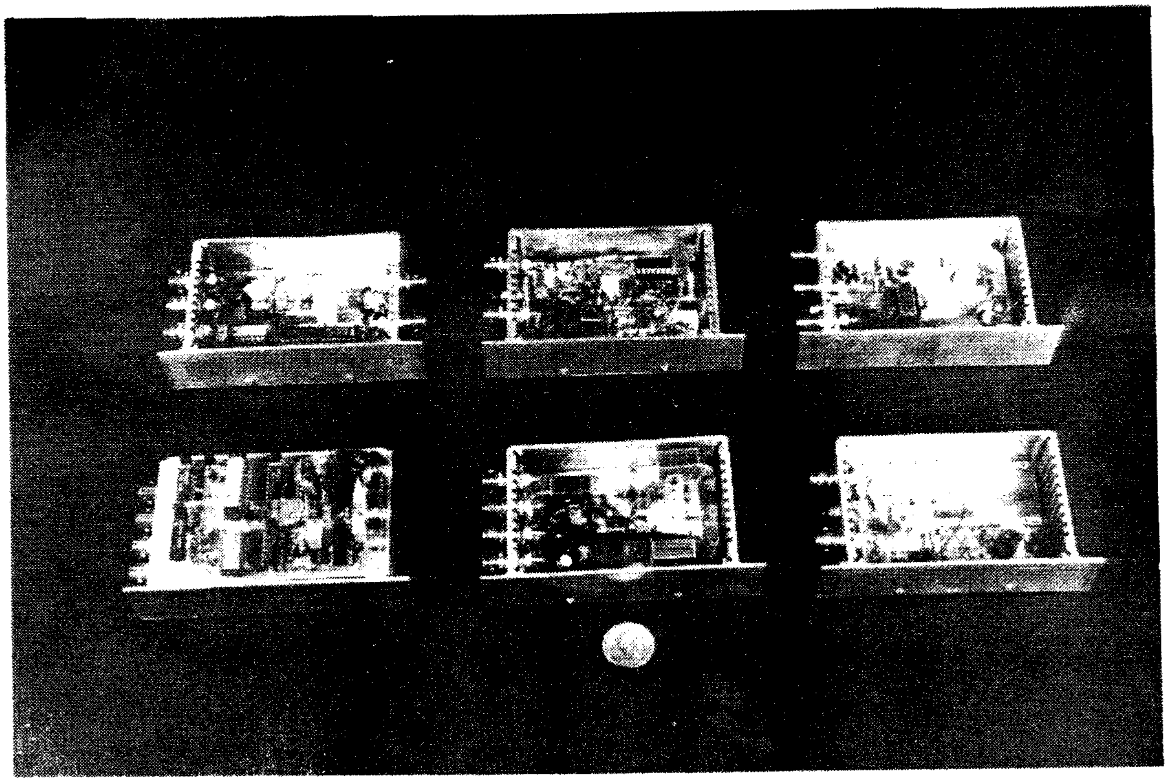

Figure 4. The Module Interiors.

Receive Modules. The receiving portion of the modulator comprises the following modules:

1. Downconverter,
2. Bandpass Automatic-Gain-Controlled (AGC) Amplifier,
3. Carrier Recovery Loop,
4. Demodulator,
5. Data Detection Module.

Downconverter. The Downconverter accepts the 70 Mhz Intermediate-Frequency (IF) signal which has either come directly from a modulator, or from a a previous downconverter which has converted a satellite-frequency signal to 70 MHz. The 70 MHz signal is mixed with a 59.3 MHz crystal-controlled oscillator signal to give the downconverted 10.7 MHz Second-IF ("2IF") output signal.

Bandpass AGC Amplifier. The Bandpass AGC Amplifier accepts the 10.7 MHz IF signal from the downconverter and filters, amplifies, and levels the signal. The amplifier section is automatic-gain controlled (AGC'd) to give an output power level which is constant to within 1 decibel (dB) for input power level variations of up to 30 dB. The channel filtering has low passband ripple, good group delay characteristics, and approximately 50 dB of rejection. Figure 6 shows the frequency response of the bandpass AGC amplifier.

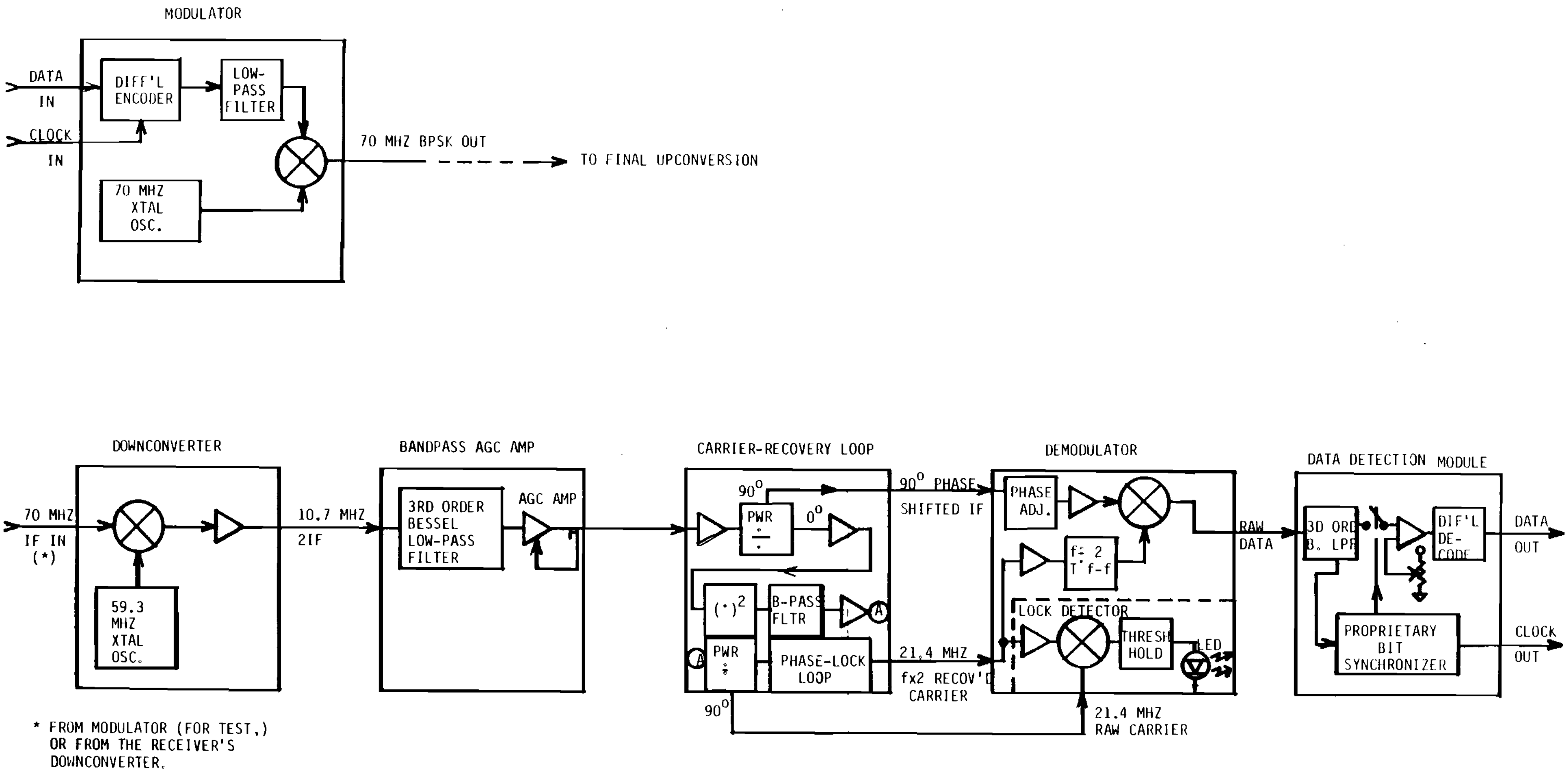

Figure 5. Functional Block Diagram of the Modem System.

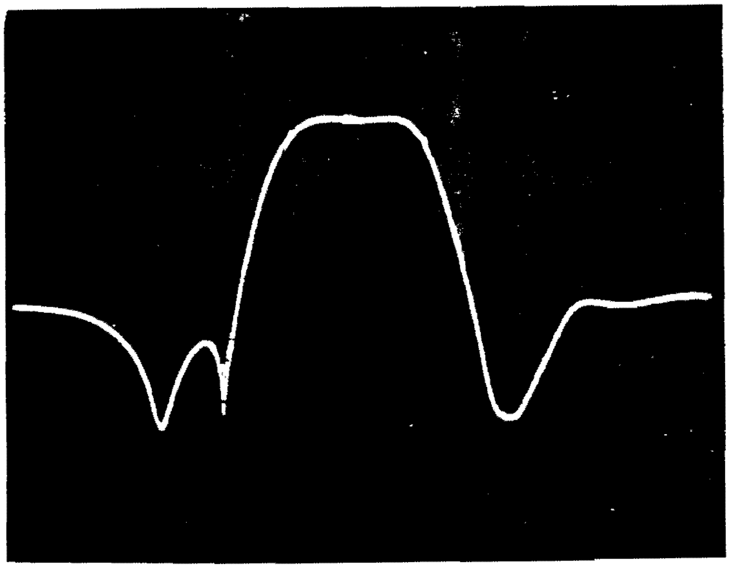

Figure 6. Filter Response of the Bandpass AGC Amplifier.

Carrier Recovery Loop. The Carrier Recovery Loop (CRL) recovers a coherent carrier from the carrierless data-bearing signal. This coherent carrier is then used in the Demodulator to demodulate to the actual (but unprocessed) data. Conceptually, the operation of the CRL is simple: since the 1,0 data multiplies the carrier sine wave by +1 or -1 in the Modulator, the first operation in the CRL is to square the signal. When this is done, the data modulation disappears since (+1) x (+1) = 1, and (-1) x (-1) = 1. The result of the squaring operation is a data-less sinewave at 2 x 10.7 = 21.4 MHz. This signal is corrupted by noise from the receiver, so a phase-lock loop (PLL) is used to closed-loop average this signal over many cycles. Thus, the output from the PLL is a "cleaned-up" 21.4 MHz sinewave which is coherent with the plus and minus sinewaves from the Modulator. However, when the PLL locks, it can lock onto either the plus or the minus sinewave, with there being no method to determine which is which. Differential encoding (in the Modulator) and Differential Decoding (in the Data Detection Module) overcome this ambiguity. This is done by causing a change in the carrier when the data is a "1", and allowing no change when the data is a zero. In this way, the ambiguity of which sinewave is the "plus" wave and which is the "minus" wave is overcome, and all that is necessary in the Differential Decoder is to determine which of "change" or "no change" has occurred. Differential encoding and decoding cause errors to appear in pairs however, so the effective SNR is degraded slightly.

The CRL Module also outputs a 90° phase-shifted IF signal for the Demodulator, and the 21.4 Mhz squared signal which is used to determine when carrier lock has occurred in the PLL.

Demodulator. The demodulator accepts the 90° phase-shifted 10.7 MHz IF signal from the Carrier Recovery Loop and phase-shifts it by an adjustable amount. The phase shift is adjusted to maximize the data-signal output from the demodulator. The 21.4 MHz signal from the CRL's PLL is divided by two fed to the mixer which performs the demodulation. The Demodulator Module also contains the Lock Detector for the PLL which is located in the CRL Module. The lock detector indicates when the PLL is locked onto the 21.4 MHz signal in the CRL.

Data Detection Module. The Demodulator output is raw (unprocessed) data. The Data Detection Module filters the data in nearly-optimum fashion -- this matched filtering minimizes the bit error rate (BER) when it is coupled with making data 1/0 decisions at precisely the right moment during each filtered bit. This decision timing is determined by the Bit Synchronizer which is a phase-lock loop that is optimized for recovering the data clock. Once the 1/0 decisions have been made, the data is differentially decoded to remove the plus/minus sinewave ambiguity as discussed previously under "Carrier Recovery Loop."

General Features

The BPSK modem is relatively simple and therefore more reliable than more complex implementations. This modem has several features to improve its performance, reliability and cost. These include:

1. High-quality filtering at 10.7 MHz. Simple, reliable, and small filters were used in the Bandpass AGC Amplifier which allowed narrow-bandpass filtering to be performed at 10.7 MHz. This has eliminated an additional downconversion to 450 KHz.

2. Use of CMOS parts. CMOS integrated circuits have been used wherever practical in the modem to increase power efficiency.

3. Use of Micamps The modem uses micamps which are monolithic (single substrate) high frequency amplifiers for IF amplification. These micamps are internally matched to 50 ohms, and since external matching components are not necessary, fewer parts are needed and reliability is increased. It should be noted that using micamps for IF amplification is more or less standard

procedure for all but the most cost-sensitive rf/if systems.

4. Use of integrated-circuit phase-lock loops. The PLL's in the Carrier Recovery Loop and the Data Detection Module's Bit Synchronizer are single-chip integrated circuits. PLL's built from individual components and using crystal-controlled oscillators give improved performance but at the cost of greater size, cost and complexity and reduced reliability.

5. Improved Bit Synchronizer. This circuit is a recent development of Cynetics' which was first applied to a Frequency-Shift Keyed (FSK) modem being used on a small satellite. This circuit uses a unique non-linearity to improve the tracking performance of the PLL within the synchronizer. The result is that the synchronizer has less tracking jitter than conventional designs, while using simpler components. Another feature is the ease with which the output clock can be adjusted for making the data 1/0 decisions at the optimum time.

6. Use of standard satellite frequencies. The 70 Mhz frequency used for the modem is the single most common IF frequency for satellite communications. It is used as the IF frequency for:

   - satellite television transmitters and receivers,
   - satellite transmission of telephone traffic,
   - satellite delivery of syndicated radio programs,
   - satellite delivery of financial data services,
   - satellite delivery of educational services,
   - satellite delivery of other data services.

   Consequently, many highly reliable, cost-effective components and subsystems are readily available.

Modem Improvements

Cynetics is planning the following improvements to the BPSK modem:

1. User-requested. Cynetics desires to match the features of the modem to the requirements of the small-satellite community. For this reason, Cynetics is gathering data on user-desired improvements and modifications to the

basic modem design.

2. Circuit Improvements. During brassboard construction, several potential circuitry improvements were found. These improvements will be implemented where they are consistent with the desires expressed by interested members of the small-satellite community.

3. Packaging Improvements. The present packaging is brassboard-style packaging. That is, the packaging has been designed for electronic function only, and not for minimum size, etc. The final packaging will be determined from user feedback.

Conclusions

BPSK is a good modulation choice for many small satellites. It represents a step toward moderately greater complexity, but much greater power efficiency, than FSK. BPSK can save at least half of the transmitter power required for FSK. This power savings can be used for increased data rates, decreased solar cell area, or increased payload power. BPSK also provides an upgrade path into the higher order modulations which may eventually be required by regulatory agencies.

Cynetics has constructed a brassboard BPSK modem for small satellite communications. This modem has several features which are appropriate for use in small satellite systems, including a relatively low parts count; CMOS circuitry; and a standard satcom IF frequency of 70 MHz. Cynetics is now gathering user comments on the modem. These comments will be used to improve the modem, which will then be made available to the small satellite community.

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