To the Graduate Council:

I am submitting herewith a thesis written by Richard I. Crutcher entitled "Analysis of a Data Isolation Technique for a Broadband Local Area Network." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

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ANALYSIS OF A DATA ISOLATION TECHNIQUE FOR A BROADBAND LOCAL AREA NETWORK

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Richard I. Crutcher

June 1988

ACKNOWLEDGMENTS

A portion of the work presented in this thesis was sponsored by Martin Marietta Energy Systems, Inc., under contract number DE-AC05-84OR21400 with the U.S. Department of Energy.

The direction of my major professor, Dr. D. W. Bouldin, and the timely review of the thesis by Dr. R. W. Rochelle and Dr. M. J. Roberts are gratefully acknowledged. I appreciate their willingness to serve on my committee.

Special acknowledgments are due my wife, Judy Crutcher, for the many hours of technical discussion, particularly concerning the mathematical concepts, for technical editing, and for teaching me TeX.

ABSTRACT

Data isolation is required in broadband cable systems to prevent unauthorized users from gaining access to the sensitive data of other users. One means of providing data isolation is to use equipment from two manufacturers to deliberately introduce an incompatibility between nonassociated users. This thesis develops the technical basis for the isolation and proposes that four layers of isolation exist when the proper equipment is chosen. Measured data from an experimental broadband LAN test network are presented to support the proposed theories. The resulting findings are that the sharing of a broadband LAN can be accomplished without compromising data security provided that protection for the nonsensitive modems is commensurate with that of the broadband network, administrative control is exercised over the sensitive modems, and appropriate data security procedures are applied to the entire network.

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CHAPTER 1

INTRODUCTION

Background Information

Widespread use of the desktop computer in the business environment has created a need for networking. Central data bases, large hard disks, multi-gigabyte optical storage, and specialized printing facilities require the interconnection of computers for cost-effectiveness and efficiency. To meet these needs, local area networks (LANs) have been developed. These LANs fall into the categories of baseband (e.g., Ethernet) and broadband radio frequency (RF) networks.

A broadband network offers many advantages for the larger corporate user. The network is configured around commercial community antenna television (CATV) technology and can offer up to 550 MHz bandwidth, providing multiple access data services, point-to-point high speed (1.544 Mbps T1 emulation) data transmission, and video teleconferencing capability. Furthermore, the tree configuration of a CATV distribution system adapts well to trunking over distances of tens of miles while providing a high fanout density in areas of user concentration.

A major disadvantage to broadband networking is the expense of installation, especially within office buildings and manufacturing facilities where special conduit or routing requirements make installing the cable a labor-intensive task. This disadvantage can be effectively offset with a design that interconnects as many users as possible to reduce the cost per user. An ideal network, from a cost viewpoint, would provide everyone at the company a connection onto the same broadband or would incorporate sharing of the broadband by multiple companies when large office complexes are involved.

Sharing of a communications resource within a company or among companies is financially attractive compared to duplication of the resources by installation of parallel systems. One consideration when using this technique is the protection of data—the LAN manager must be assured that sensitive data are not accessible to users who do not have the proper authorization.

Isolation Technique

The method of isolation proposed in this thesis uses broadband modem equipment from two manufacturers to introduce a deliberate incompatibility between nonassociated users. Vendor products from Sytek and Ungermann–Bass were chosen because both companies are well established in this field and offer a wide selection of broadband modem equipment. These manufacturers use different bandwidths, protocols, and modulation methods to transmit the data between users, and initial analysis of the equipment specifications suggested that an isolation would exist. The Sytek modem chosen was the model 2502 packet communications unit (PCU), a frequency programmable modem with two RS-232 user ports. The Ungermann–Bass network was centered around the network interface unit (NIU) model NIU-180, a modem providing eight RS-232 ports.

Further analysis indicated that a minimum of four independent levels of isolation were achievable: (1) frequency separation on the broadband cable, (2) differences in RF bandwidth and modulation, (3) detection of the broadband signal to recover the digital data, and (4) software protocols implemented for packet transmission control by each system. An in-depth analysis was made for each of these areas. Techniques used by each manufacturer were researched, and, where appropriate, analytical models were developed to determine the theoretical isolation achieved between the systems. Because of proprietary restrictions, schematic diagrams of the equipment were unavailable. However, sufficient information was obtained to analyze each of these areas through circuit tracing and reference to partial diagrams of an older model modem.

The equipment was next incorporated into a broadband LAN test system. This test setup was centered around a two amplifier midsplit 300-MHz broadband network. The Ungermann–Bass equipment included two NIU-180 modems, a personal computer card NIU-2361A that served as the network controller, and a model 5517A frequency translator. The Sytek equipment consisted of two model 2502 PCU modems and a model 2500 downloader for providing initialization of the PCUs. The system was monitored by an array of test equipment including an RF spectrum analyzer (with plotting capability), an oscilloscope, and a digital logic analyzer. Measurements were made on the system to verify that the proposed levels of isolation did exist and to establish the amount of isolation that could be achieved. Additionally, the network was operated for extended communications sessions while monitoring various points in the Sytek modem to determine the data characteristics at those points.

The application for which this study was performed was primarily concerned with the isolation achieved when going from the Ungermann–Bass network to the Sytek network. The primary analysis was made in this direction, as were the majority of the hardware tests. The isolation provided by each of the levels is subject to the superposition principle, and results measured in one direction can be applied to the other. Because in-depth analysis and measurements were not performed in the Sytek to Ungermann–Bass direction, total isolation cannot be guaranteed. Testing from the Sytek input to the Ungermann–Bass output indicated that isolation existed, but a layer-by-layer analysis is not provided.

Chapter Contents

The theoretical analyses of the four isolation levels are developed in Chapter 2. Isolation through frequency separation is analyzed from the viewpoint of the RF characteristics of a broadband cable system, considering the effects of nonlinear operation in addition to normal operating parameters. The RF bandwidth and modulation differences are examined to determine their effects on isolation. The detection of the digital data is next analyzed from the perspective of both the available signal that is recovered and the manner in which these digital data are processed. Finally, the software protocols for the packet transmissions are compared. Chapter 3 presents the measurements made on the operating networks. The test data for each isolation level appear in the same order as the theoretical analyses of Chapter 2. Where applicable, comparisons are made between the theoretical results and the measured data. In Chapter 4, a summary and conclusions of the project are given.

CHAPTER 2

THEORETICAL ANALYSIS

The theoretical analysis of the isolation achievable from the mixed-modem technique is presented in this chapter. The specifications and characteristics of the modems are presented to provide the data required for several of the calculations. Analysis is performed on each of the four proposed layers of isolation, taken in the order of signal flow from the broadband cable to the user serial ports.

A simplified block diagram of the Sytek modem is shown in Figure 2.1. The diagram is useful in locating the layers of isolation (indicated by circled numbers) to be analyzed. Layer 1, the RF frequency separation, is associated with the broadband cable and RF stages of the modem. The RF bandwidth and modulation differences occur in layer 2, in the receiver section. Layer 3 is the recovery of the digital data at the broadband serial interface of the modem. Isolation from the software transmission protocols is indicated on the diagram as layer 4.

Characteristics of the Modems

The first layer of isolation is primarily obtained from characteristics of the broadband cable system, but the modem characteristics have a secondary influence on the isolation. The remaining three layers are entirely functions of the modem equipment. Differences found in equipment specification sheets from Ungermann–Bass and Sytek provided motivation for selecting these two networks for isolation testing. A summary of pertinent equipment specifications is presented in Table 2.1.[1,2]

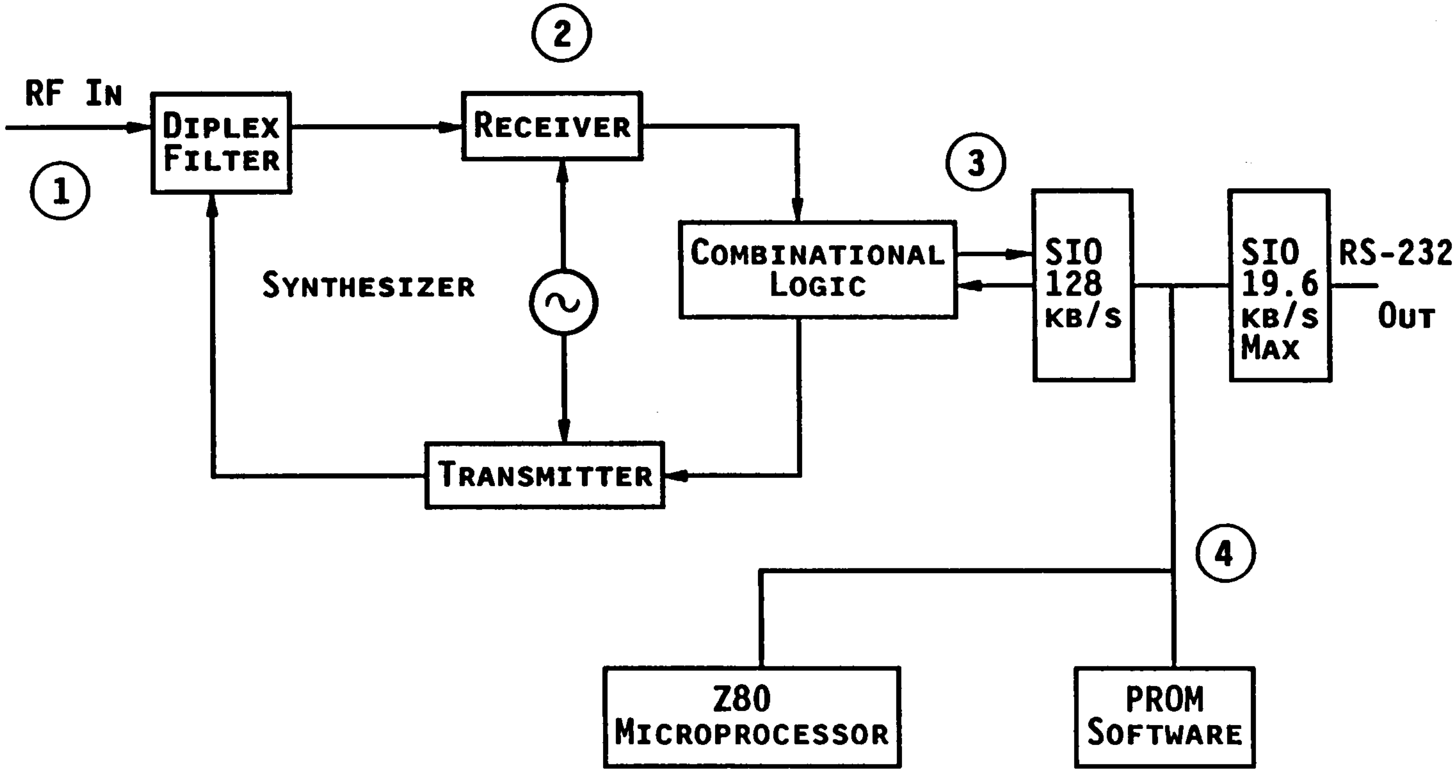

Figure 2.1. Simplified functional block diagram for the Sytek modem.

Table 2.1 Specifications for the Ungermann–Bass and Sytek equipment

Parameter	Ungermann–Bass	Sytek
Transmitter		
Channel spacing	6 MHz	300 kHz
Frequency deviation (kHz)	—	±29 ±4
Frequency stability	±10 kHz	±0.002%
Modulation technique	Duobinary AM/PSK	Phase continuous FSK
Transmit power (dBmV)	+40 to +56	+46[a]
Carrier "off" level[b] (dB)	60	50[c]
Spurious emissions[b] (dB)	60	—
Out-of-band emissions[b] (dB)	45[d]	50[c]
	60[e]	
Receiver		
Input level (dBmV)	–7 to +13	–8 to +4
Receiver sensitivity[f] (dBmV)	—	–20
Adjacent channel rejection[b] (dB)	10[c]	20
Translator		
Bandwidth (MHz)	5 at ±3 dB	6 at ±3 dB
	7 at –40 dB	
Frequency stability (kHz)	±750	±1.6
Offset frequency (MHz)	192.250	192.250
Input level (dBmV)	–10 to +10	–20 to +2
Spurious emissions[b] (dB)	60	60
Third-order intermodulation distortion[b] (dB)	55	40

[a]Nominal.
[b]Below peak carrier output.
[c]Minimum.
[d]Referenced to edge of band.
[e]Referenced to full channel.
[f]For 20 dB quieting of all channels.

The first listing in Table 2.1, under transmitter, is channel spacing. The channel spacing is a measure of the difference between two adjacent unmodulated carrier frequencies. It serves as an approximate indication of required channel bandwidth, and spectral power envelope plots (to be presented in Chapter 3) will verify that the Ungermann–Bass bandwidth is 6 MHz and the Sytek bandwidth is 300 kHz. This bandwidth difference will affect the isolation obtained in the RF bandwidth analysis. Frequency deviation and stability have a secondary effect on the RF modulation and frequency separation layers, respectively.

The next item in the table is modulation technique. The Ungermann–Bass modem uses a duobinary amplitude-modulated, phase-shift-keyed (AM/PSK) modulation technique. The Sytek network uses a phase-continuous, frequency-shift-keyed (FSK) modulation. These differences are the foundation for isolation by RF modulation.

Transmit power, carrier "off" level, spurious emissions, and out-of-band emissions are all directly related to the performance of the frequency separation layer.

The receiver characteristics in the table include input level, receiver sensitivity, and adjacent channel rejection. Each of these makes either a negative or a positive contribution to the frequency separation layer. Adjacent channel rejection has an additional role in the bandwidth isolation layer because the adjacent channel rejection gives an indirect indication of the receiver bandwidth characteristics.

The translators, while not specifically modem equipment, are a key portion of the broadband network. Bandwidth, frequency stability, offset frequency, input level, spurious emissions, and third-order intermodulation distortion will all have either a primary or secondary influence on frequency separation isolation.

With these equipment specifications documented, an analysis of the four isolation layers will be performed.

Frequency Separation

The first layer of separation proposed by the mixed-modem technique exists primarily as a function of the broadband cable rather than the modem devices. Normal broadband cable operation places nonassociated modem systems on different frequencies. The separation is a form of frequency division multiplexing (FDM) on the cable and provides excellent isolation in a properly operating system.

Figure 2.2 shows a hypothetical spectrum for a midsplit broadband cable system with two operational data channels. The four carriers represent systems A and B with forward and reverse channels and a translator frequency offset of 192.25 MHz. The carriers of each system are separated in frequency, and each receiver only responds to the signal intended for it. The spectrum in Figure 2.3 illustrates a more typical broadband system with three data channels and four video channels. Frequency separation still provides an isolation among channels. A nonlinearity introduced into the broadband causes the spectrum to appear as in Figure 2.4. The original carrier frequencies are present, but numerous intermodulation products that were not present in the linear system have appeared. These intermodulation products are the result of combinations of the fundamental carriers and their harmonics.

These figures provide an introduction to the effects of intermodulation but present only relative values of magnitude. The actual magnitudes will depend on carrier levels and the characteristics of the nonlinear function. Spectral plots

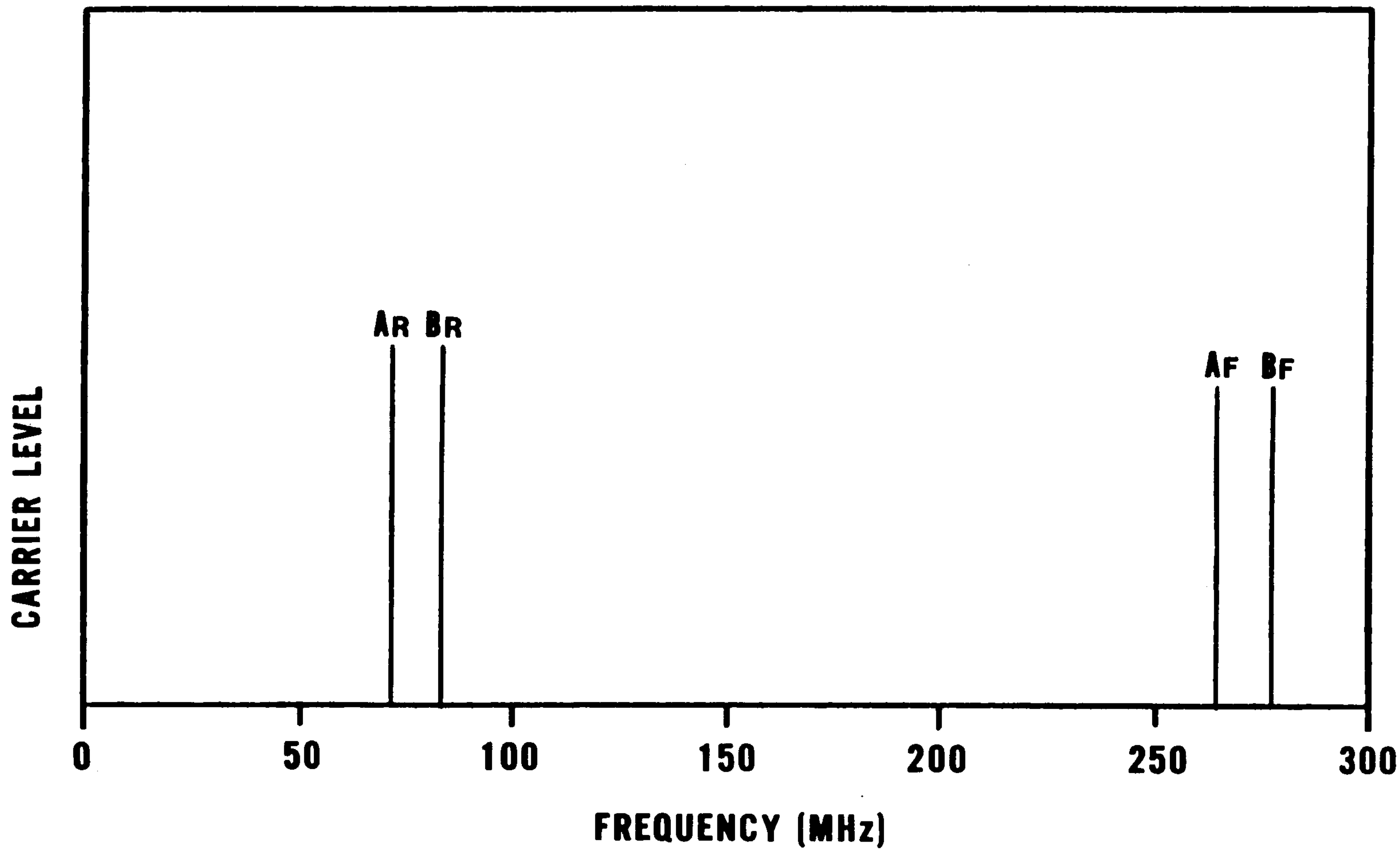

Figure 2.2. Broadband cable spectrum with two data channels.

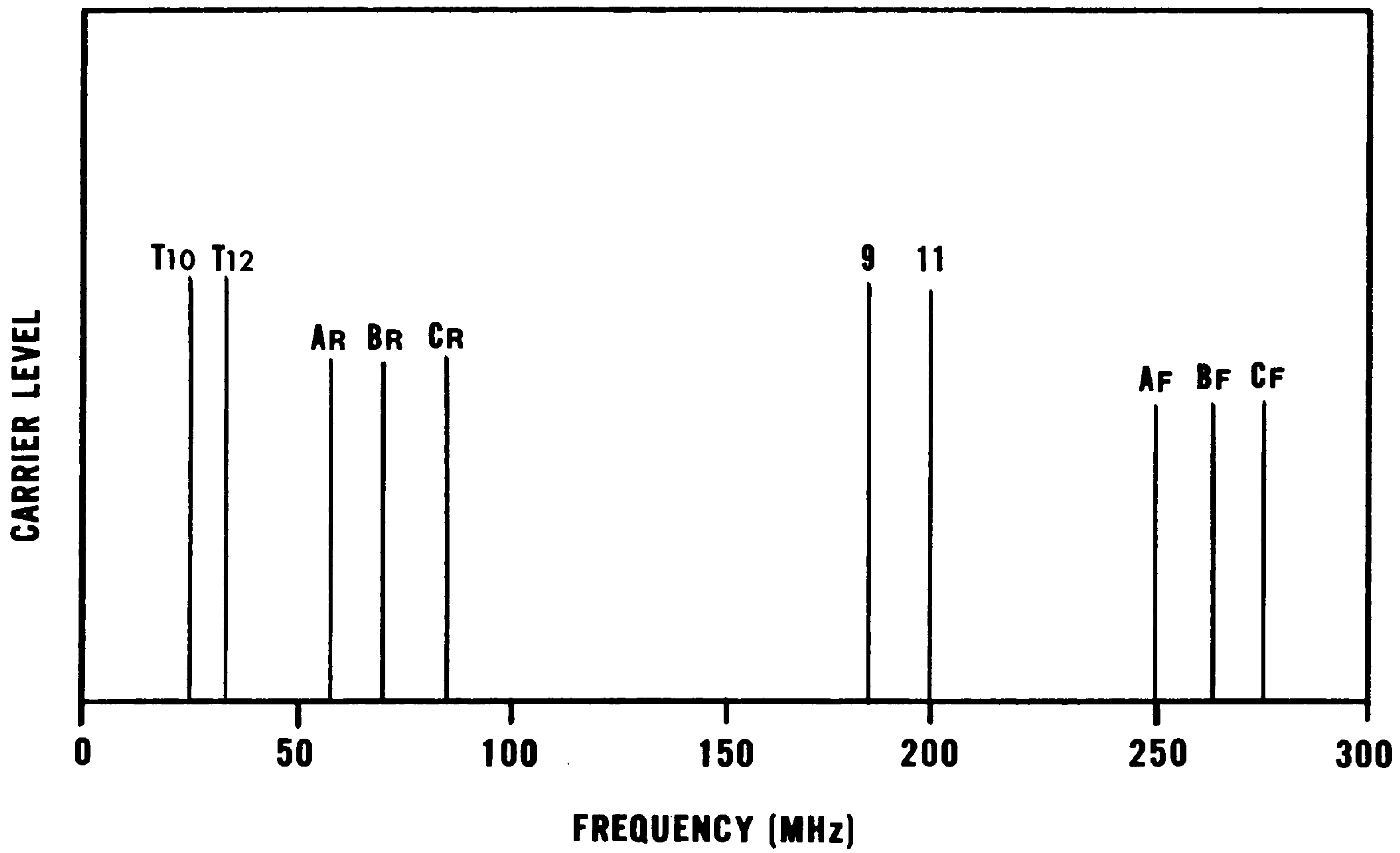

Figure 2.3. Broadband cable spectrum with three data channels and four television channels.

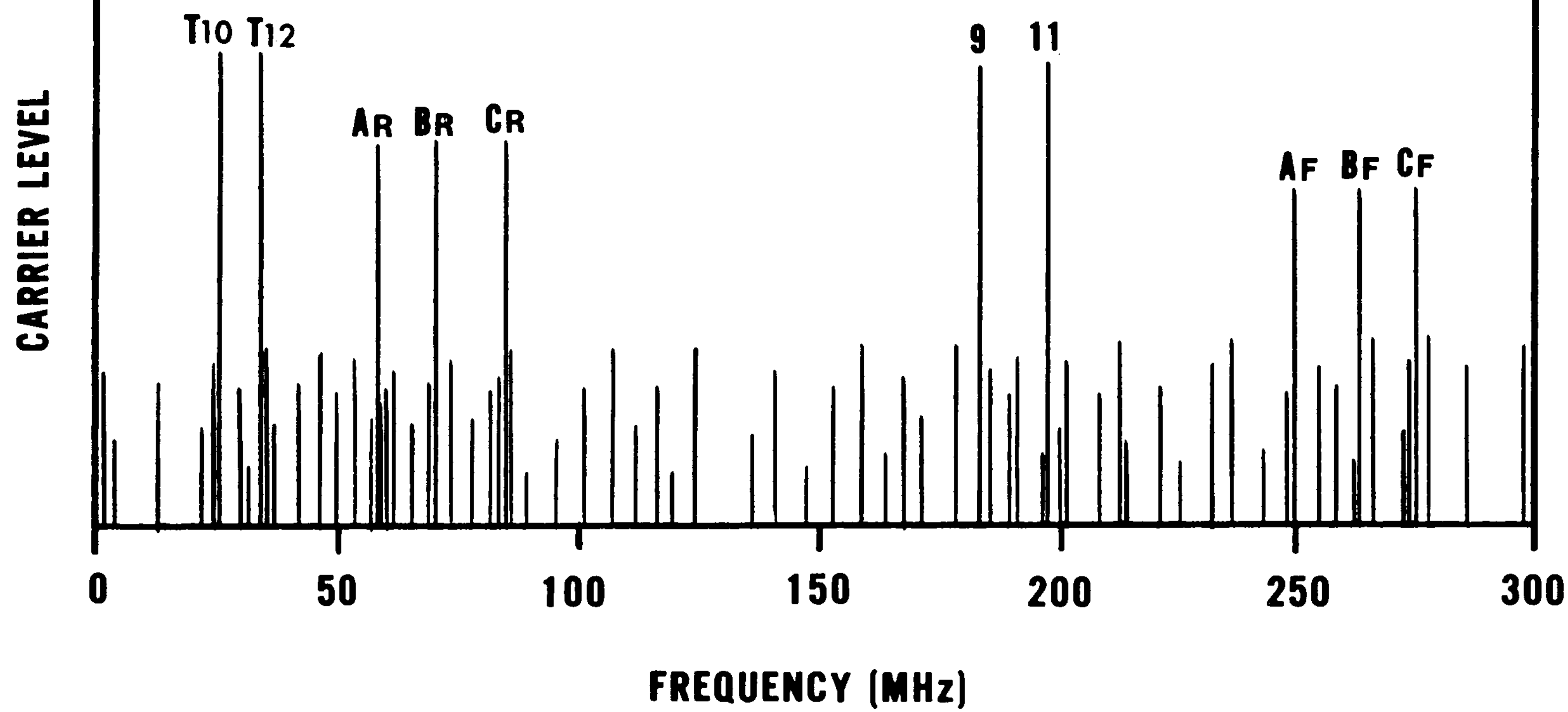

Figure 2.4. Broadband cable spectrum with three data channels and four television channels in the presence of nonlinear distortion.

modeling an operational system will be presented after a mathematical background is developed.

Time-Domain Analysis of a Nonlinearity Model

The classical presentation of nonlinear mixing centers around various combinations of the fundamental frequencies and their harmonics. An intermodulation product is characterized in the form of

$$n_1 f_1 \pm n_2 f_2 \pm n_3 f_3 \pm \ldots$$

where each f represents a signal frequency, and each n is the harmonic multiplier for that frequency. Using this model, the order of an intermodulation product is defined as the summation of the n's for that product.

The application of this model leads to second-order products $(f_1 \pm f_2)$ and third-order products $(2f_1 \pm f_2, 2f_2 \pm f_1, f_1 \pm f_2 \pm f_3)$. Higher order products are obtained in a similar manner. The third-order intermodulation product of $f_1 \pm f_2 \pm f_3$ is known as triple beat and is especially troublesome in broadband cable systems that have high-level, closely spaced carriers.[3] Because of the wide spacings that are obtained from second-order mixing, these products are more troublesome in broadband systems than in narrowband networks. Broadband trunk amplifiers are generally designed to reduce even-order products, but distortions in receiver front-end amplifiers can produce even-order products whose existence cannot be ignored when performing an analysis.

The equation produces what appears to be a limitless number of possible intermodulation products. The primary utility of the equation is the ability to predict the frequencies at which intermodulation products can occur. Very early analysis in the study was performed with a modified version of

INTERMD, a computer program for calculating intermodulation frequencies in radio communications networks.[4] The modified program eliminated repeater frequency shifts, assumed wider receiver bandwidths, and inserted the even-order intermodulation products (even-order products fell outside the frequency band of interest in the narrowband system modeled by INTERMD). The program determined that several hundred unique mixing products were possible on a cable with moderate channel loading. Fully loaded cables can have thousands of possible intermodulation products.

The intermodulation equation can predict the possible occurrence of these products, but provides no way of determining which products have sufficient amplitudes to cause interference. The only rule typically given is that an amplitude will decrease as the order of the product increases. Because of the deficiency in calculating amplitudes, a nonlinearity model was developed for verification of the distortion results in the time domain.

Figure 2.5a represents a simple nonlinear model. The model consists of a time varying input voltage, a nonlinear device, and a load resistance across which the output is developed. The transfer characteristic of such a system is shown in Figure 2.5b. If the nonlinear characteristics of the device are assumed continuous, then v_o may be expanded as a power series of v_i.[5] Under these conditions,

$$v_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \ldots + a_n v_i^n,$$

$$\text{where } v_i = \cos\omega_1 t + \cos\omega_2 t + \cos\omega_3 t + \ldots + \cos\omega_m t.$$

Applying this relation to a single carrier frequency, we obtain

$$v_o = a_1 \cos\omega t + a_2 \cos^2\omega t + a_3 \cos^3\omega t + a_4 \cos^4\omega t + a_5 \cos^5\omega t +$$

$$\text{higher order terms.}$$

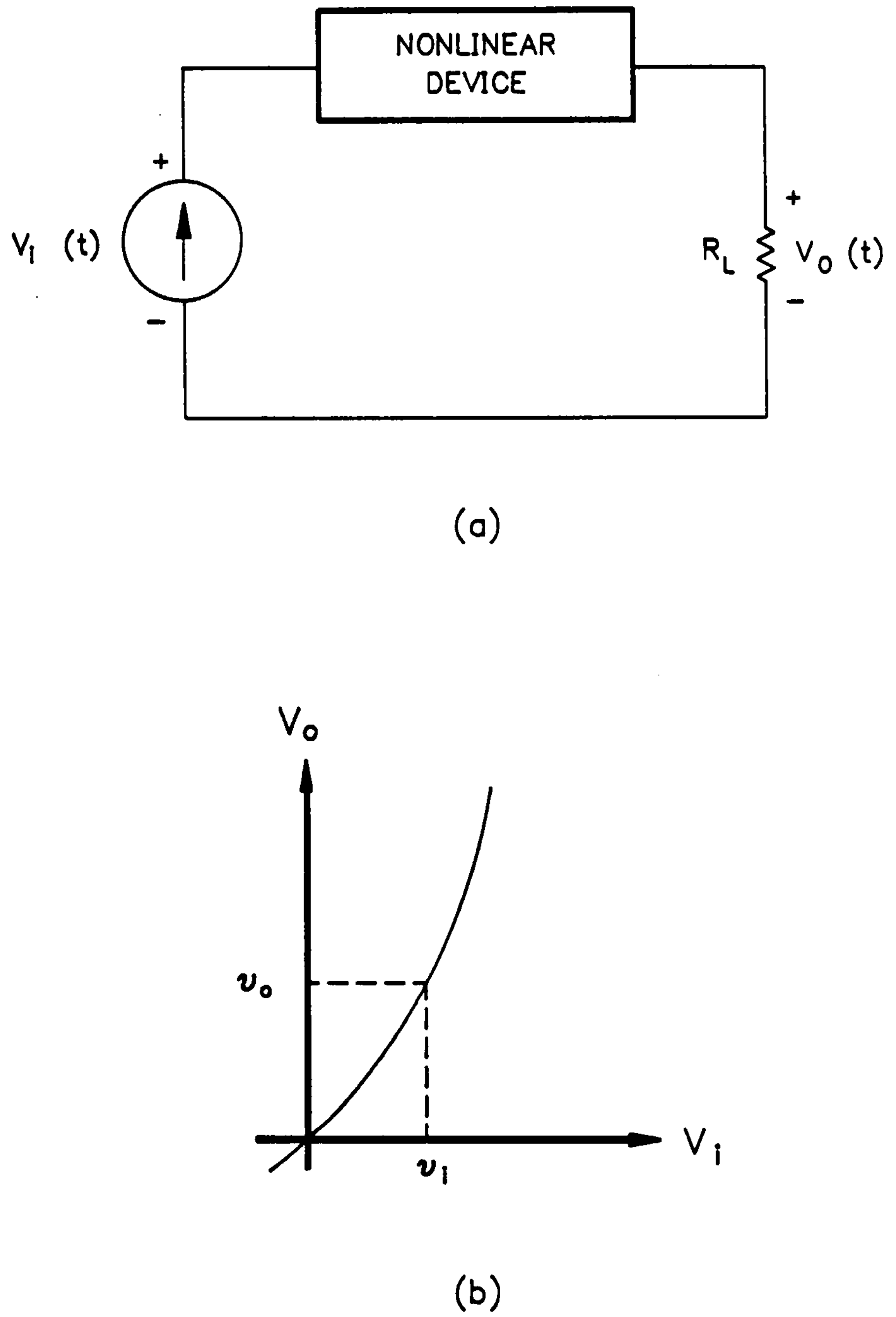

Figure 2.5. Simple nonlinear model for generation of intermodulation products.

Using the trigonometric identities for powers of cosines listed in Table 2.2 and combining the results lead to

$$v_o = \frac{1}{2}a_2 + \frac{3}{8}a_4 + \left(a_1 + \frac{3}{4}a_3 + \frac{5}{8}a_5\right)\cos\omega t +$$
$$\left(\frac{1}{2}a_2 + \frac{1}{2}a_4\right)\cos 2\omega t + \left(\frac{1}{4}a_3 + \frac{5}{16}a_5\right)\cos 3\omega t + \left(\frac{1}{8}a_4\right)\cos 4\omega t +$$
$$\left(\frac{1}{16}a_5\right)\cos 5\omega t + \text{higher order terms.}$$

Each additional term will contribute a frequency equal to the fundamental times the order plus supplementary coefficients at the lower frequencies. A significant result demonstrated by the single-frequency case is that harmonics of the fundamental frequency can be generated when applied to a nonlinearity.

Applying the power series representation of v_o to a two-frequency system results in

$$v_o = a_1\left(\cos\omega_1 t + \cos\omega_2 t\right) + a_2\left(\cos\omega_1 t + \cos\omega_2 t\right)^2 +$$
$$a_3\left(\cos\omega_1 t + \cos\omega_2 t\right)^3 + \text{higher order terms.}$$

Again, using the trigonometric identities of Table 2.2 and combining terms yield

$$v_o = a_2 + \left(a_1 + \frac{9}{4}a_3\right)\cos\omega_1 t + \left(a_1 + \frac{9}{4}a_3\right)\cos\omega_2 t +$$
$$\frac{1}{2}a_2\cos 2\omega_1 t + \frac{1}{2}a_2\cos 2\omega_2 t + \frac{1}{2}a_2\cos\left(\omega_1 - \omega_2\right)t +$$
$$\frac{1}{2}a_2\cos\left(\omega_2 - \omega_1\right)t + a_2\cos\left(\omega_1 + \omega_2\right)t + \frac{1}{4}a_3\cos 3\omega_1 t +$$
$$\frac{1}{4}a_3\cos 3\omega_2 t + \frac{3}{4}a_3\cos\left(2\omega_1 - \omega_2\right)t + \frac{3}{4}a_3\cos\left(2\omega_1 + \omega_2\right)t +$$
$$\frac{3}{4}a_3\cos\left(\omega_1 - 2\omega_2\right)t + \frac{3}{4}a_3\cos\left(\omega_1 + 2\omega_2\right)t + \text{higher order terms.}$$

Table 2.2 Trigonometric identities used in the power series nonlinearity model

Product expression	Summation equivalence
$\cos^2 \omega t$	$\frac{1}{2}\cos 2\omega t \; + \; \frac{1}{2}$
$\cos^3 \omega t$	$\frac{1}{4}\cos 3\omega t \; + \; \frac{3}{4}\cos \omega t$
$\cos^4 \omega t$	$\frac{1}{8}\cos 4\omega t \; + \; \frac{1}{2}\cos 2\omega t \; + \; \frac{3}{8}$
$\cos^5 \omega t$	$\frac{1}{16}\cos 5\omega t \; + \; \frac{5}{16}\cos 3\omega t \; + \; \frac{5}{8}\cos \omega t$
$\cos \omega_1 t \cos \omega_2 t$	$\frac{1}{2}\cos(\omega_1 + \omega_2)t \; + \; \frac{1}{2}\cos(\omega_1 - \omega_2)t$

The results of the two-tone intermodulation equation lead to several observations. v_o is composed of a dc term, fundamental terms, second harmonic terms, second-order cross-product terms, third harmonic terms, and third-order cross-product terms. The third-order intermodulation products come from the v_i^3 term of the series expansion and receive their name from the relationship to a third-order equation. If the series expansion is continued, fourth-, fifth-, and higher-order terms will result. Additionally, contributions will be made to the coefficients of the lower-order terms. In a physical system, stray reactances and active device frequency limitations reduce the contributions of the higher-order terms. Without these physical limitations on frequency, the contributions from higher orders still decrease as the fractional coefficients become smaller. The combination of decreasing coefficients and high-frequency attenuation allows the lower orders of harmonics and intermodulation products to contain more power and to create a greater interference problem than the higher orders.

Before leaving this model, one other consideration should be addressed. The series expansion of v_o left the coefficients in terms of a_n. These coefficients adjust the power series to fit a particular nonlinear function and the amplitude of any order will depend upon the characteristics of the nonlinearity. Some terms may become large while others approach zero. A given nonlinear function can be analyzed using this model, but establishing precise amplitudes requires extensive calculation.

The intermodulation model developed in this section derives an output when multiple frequencies are mixed by a nonlinear device. For an ideally linear broadband cable system, only the fundamental carrier frequencies are present. However, amplifiers and passive components are less than ideal and produce some nonlinearities. An amplifier exhibits a limited power output and operates with a linear input/output relationship only for output values below the point at which output compression begins. The amplitude of intermodulation products depends on the levels of the fundamental carriers and the extent of nonlinear operation.

A nonlinearity is generally characterized by the concept of the intercept point, which is the level at which the fundamental and the intermodulation products have equal amplitudes.[6] The intercept point is commonly considered a theoretical point in amplifiers because gain compression limits the output power to a level less than the intercept power. Other broadband products, such as frequency translators, exhibit intercept points within the output limitations of the device. Because translators are required on midsplit broadband systems with data channels, care must be taken to control the carrier levels and maintain linearity.

Intercept points are determined by the order of the distortion, the drive of the carrier levels, and the suppression of the distortion products for that drive level. The slope of the line for intermodulation products is determined by the order of the distortion. A third-order distortion has a slope of three, and a fifth-order distortion has a slope of five. Thus an increase in fundamental carrier levels of 1 dB raises the third-order distortion products by 3 dB. Figure 2.6 is a graphical representation of the intercept point concept. The linear output is extrapolated to extend beyond the signal level that is normally obtained from the device. The second- and third-order products are plotted based on measurements made at lower levels. The point on the graph where a distortion line intersects the output line is the intercept point for that order. Intercept values for a given device or system can be determined by plotting the measured values.

Standard engineering practices dictate that cross modulation and triple beat on a broadband cable should be 59 dB below the signal levels.[7] Operation

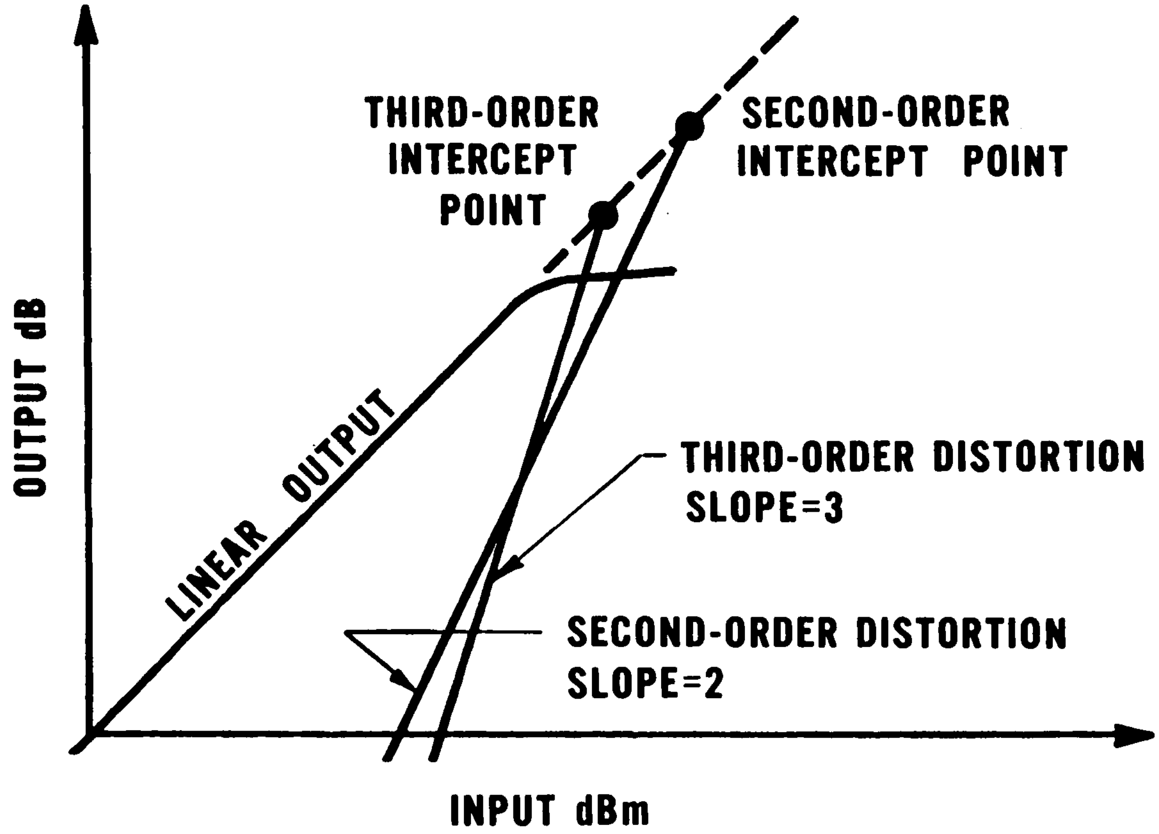

Figure 2.6. Intercept point extrapolation for amplifier distortion vs input power.

in this region ensures isolation between modems on different frequencies. It is important to note however that nonlinear operation can bypass the first layer of isolation.

Development of a Frequency-Domain Broadband Model

The time-domain nonlinearity model developed in the previous section demonstrates the creation of intermodulation products and characterizes the amplitude of each product term. In practice, intermodulation on an operating broadband system is typically measured using an RF spectrum analyzer. A computer model of a spectrum analyzer and broadband cable network was created around a fast Fourier transform (FFT) program that was modified from a published subroutine.[8] A listing of the program is given in the Appendix.

The nature of the FFT algorithm requires that data array boundaries fall on a multiple of 2^n. The model is configured to present positive frequencies in the range from 0 to 500 MHz (scaled to 1 MHz per sample). However the FFT is actually calculating 16,384 samples, with half being lost to "negative" frequency and the remainder being required to prevent aliasing from higher-order harmonics.

The limitation in resolution of 1 MHz per sample is not unreasonable because it parallels the filter bandwidth resolution encountered in an RF spectrum analyzer. The sampled frequencies must be integers to avoid a spreading of the carrier signal. This constitutes a minor error as television frequencies are typically positioned with the visual carrier 1.25 MHz above the lower edge of the band and the aural carrier 4.5 MHz above the visual carrier. For purposes of the model, visual carriers are placed 1 MHz above the band edge, and the aural carriers are 5 MHz above the visual carrier frequencies. This approximation is justified because the channels chosen for the model are hypothetical and because intermodulation products can be identified in terms of the chosen fundamental carrier frequencies. In the event that 0.250 MHz resolution is needed for placing actual carrier frequencies, the model can be adjusted with a 4:1 scaling factor. The penalty will be a reduction in the harmonic rejection resulting from the higher sampling rate, and aliasing by the high-order intermodulation products may become apparent.

The vertical scale of the model has a 90 dB dynamic range. This exceeds the available range of commercial RF spectrum analyzers operating at wide filter bandwidths. Earlier versions of the simulation inserted an analyzer noise floor at approximately 65 dB below peak carrier level, as would be found in a physical analyzer. In those same applications, the noise floor is an impairment and requires that external bandpass filters be used when reading low-level intermodulation products. The noise floor was therefore eliminated from the analyzer model to aid in the measurement of low-amplitude products. This variation in the model allows intermodulation products near the bottom of the scale to be seen even though these products are below the noise floor of both the broadband cable amplifiers and the receivers.

The top of the scale for the analyzer model is determined in one of two manners. Some plots reference "0 dB" to the peak carrier level, which for purposes of calculation is 1 volt. (It is common practice to reference harmonics and intermodulation products to peak carrier level rather than expressing them in absolute dBm or dBmV.) Other plots show carrier levels that are increased as a method of triggering the nonlinear distortions. For these plots, the top of the scale is +10 dB, referenced to the original peak carrier level. The scale provides 10 dB of headroom on the display so that the intermodulation reference does not shift downward each time the carrier level is increased. The values for the scale are included on each plot, and levels should present no confusion. In practice, the top of the scale ranges from 0 to +60 dBmV, depending on the measurement location with respect to system components.

A broadband cable network for an industrial or business application will contain both data channels and video teleconferencing channels. A possible frequency allocation for such a system is presented in Table 2.3. The broadband system contains an Ungermann–Bass forward data channel at 268 MHz and a Sytek forward data channel at 277 MHz. Forward video teleconferencing is provided by television channels 7 and V. The reverse channels include Ungermann–Bass and Sytek data at 75 and 84 MHz, respectively, and television channels T8 and T12. The carrier frequencies have been adjusted to integer values to maintain compatibility with the FFT model. Carrier power levels are expressed in dBV and maintain the proper relationships for reduction of aural and data carriers with respect to the peak visual carrier level. Shown in Figure 2.7 is the spectrum for this broadband cable system. The spectrum presents an ideally linear network, in as much as only the carrier frequencies are present. Each channel carrier makes a contribution at its allocated frequency, and isolation for the frequency separation layer is at a maximum.

If a broadband network could be perfectly linear, there would be no reason to consider further layers of isolation. Unfortunately, a physically realizable broadband network does contain nonlinearities. Trunk amplifiers, receiver amplifiers, and corroded connectors all add some nonlinear distortion. Therefore, when modeling the broadband, it is necessary to determine what forms the nonlinearities will take, either during normal operation or under fault conditions. Typical cases include soft gain compression, clipping, and rectification.

Table 2.3 Frequency and power allocations for a hypothetical broadband cable network

Frequency[a]	Power (dBV)	Purpose
12	0	Ch. T8 visual carrier
17	–15	Ch. T8 aural carrier
36	0	Ch. T12 visual carrier
41	–15	Ch. T12 aural carrier
75	–15	Ungermann–Bass reverse data
84	–10	Sytek reverse data
175	0	Ch. 7 visual carrier
180	–15	Ch. 7 aural carrier
268	–15	Ungermann–Bass forward data
277	–10	Sytek forward data
289	0	Ch. V visual carrier
294	–15	Ch. V aural carrier

[a]Frequencies are adjusted to the nearest integer value for compatibility with the FFT model.

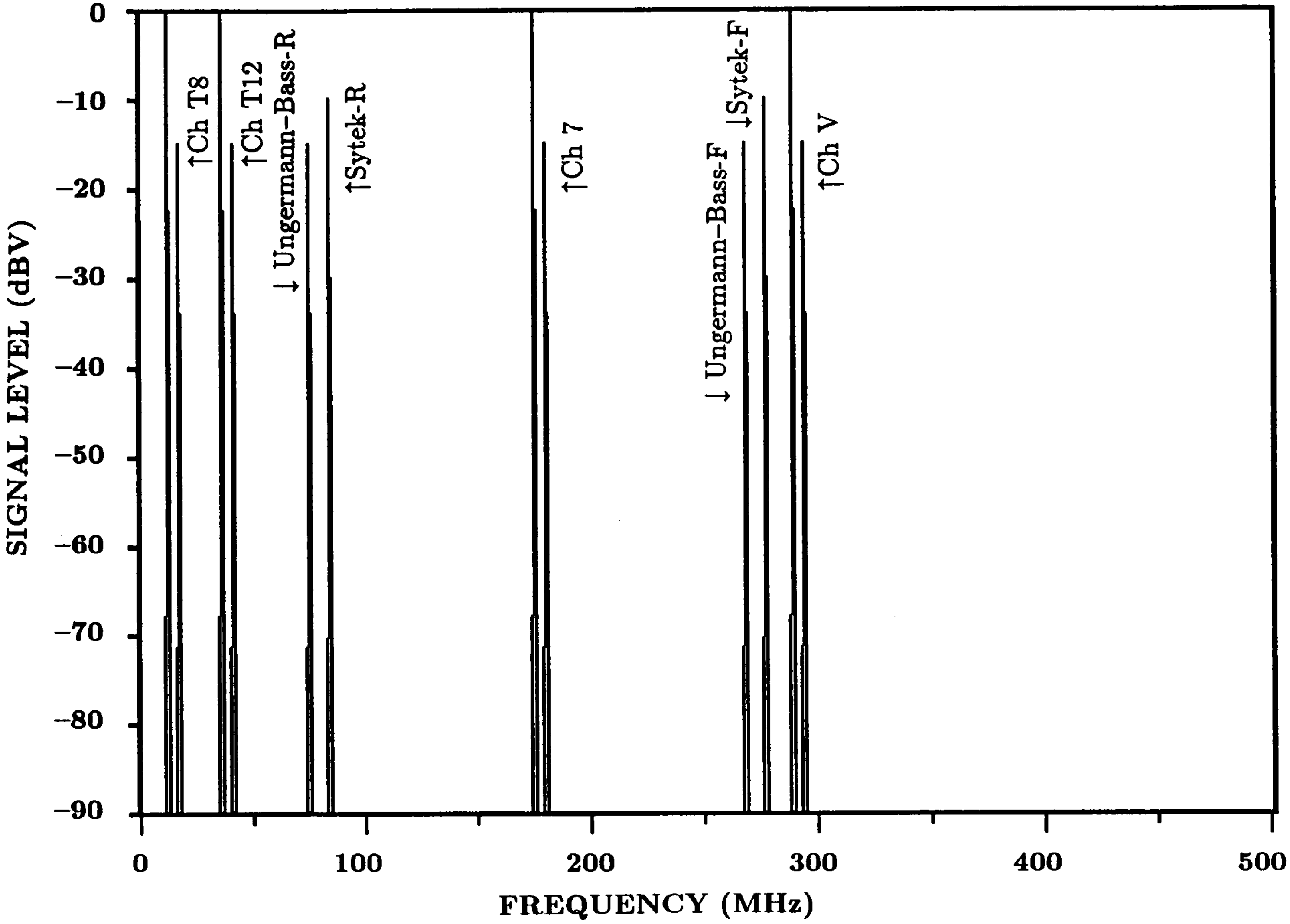

Figure 2.7. Spectrum of an ideal broadband cable with no distortions.

Soft gain compression is a common nonlinearity in a broadband communications network. High power levels applied to an amplifier cause a slight compression of the output characteristic. Trunk amplifiers driven at high output levels exhibit this distortion on cable systems with heavy channel loading. Receiver front-end amplifiers likewise go into compression when high-level signals are applied. Figure 2.8 represents the spectrum of the broadband network operating under compression distortion. The carrier level of Channel 7 has been increased 3 dB beyond the compression threshold to simulate a fault in the modulator. Because 12 frequencies are involved in the mathematical expansion, numerous distortion products are generated. The peaks of the mixing outputs are approximately 50 dB below the original carrier reference. The major impact of this distortion is to effectively raise the noise floor of the broadband system.

A more serious compression distortion is represented in Figure 2.9. Channel 7 has been raised a full 10 dB above the compression threshold. This range may seem unreasonable, but such excursions in carrier amplitude have occurred when a modulator level was established on a system with intermittent lossy connections that later improved. The entire group of intermodulation products has moved upward so that the stronger peaks fall 30 dB below carrier reference. These distortions are of sufficient amplitude to cause interference.

Modeling a system with 12 carriers presents difficulty in identification of the individual distortion products. Figure 2.10 shows similar distortion conditions with only two carriers. Carrier f_1 has been raised 10 dB above the compression threshold, and the nonlinearity factor has been increased slightly to compensate for the lower total power level obtained from two signals. The stronger intermodulation products have been labeled for easy identification. For this particular nonlinearity model, harmonics of f_1 are strong, as are the second-order sum and

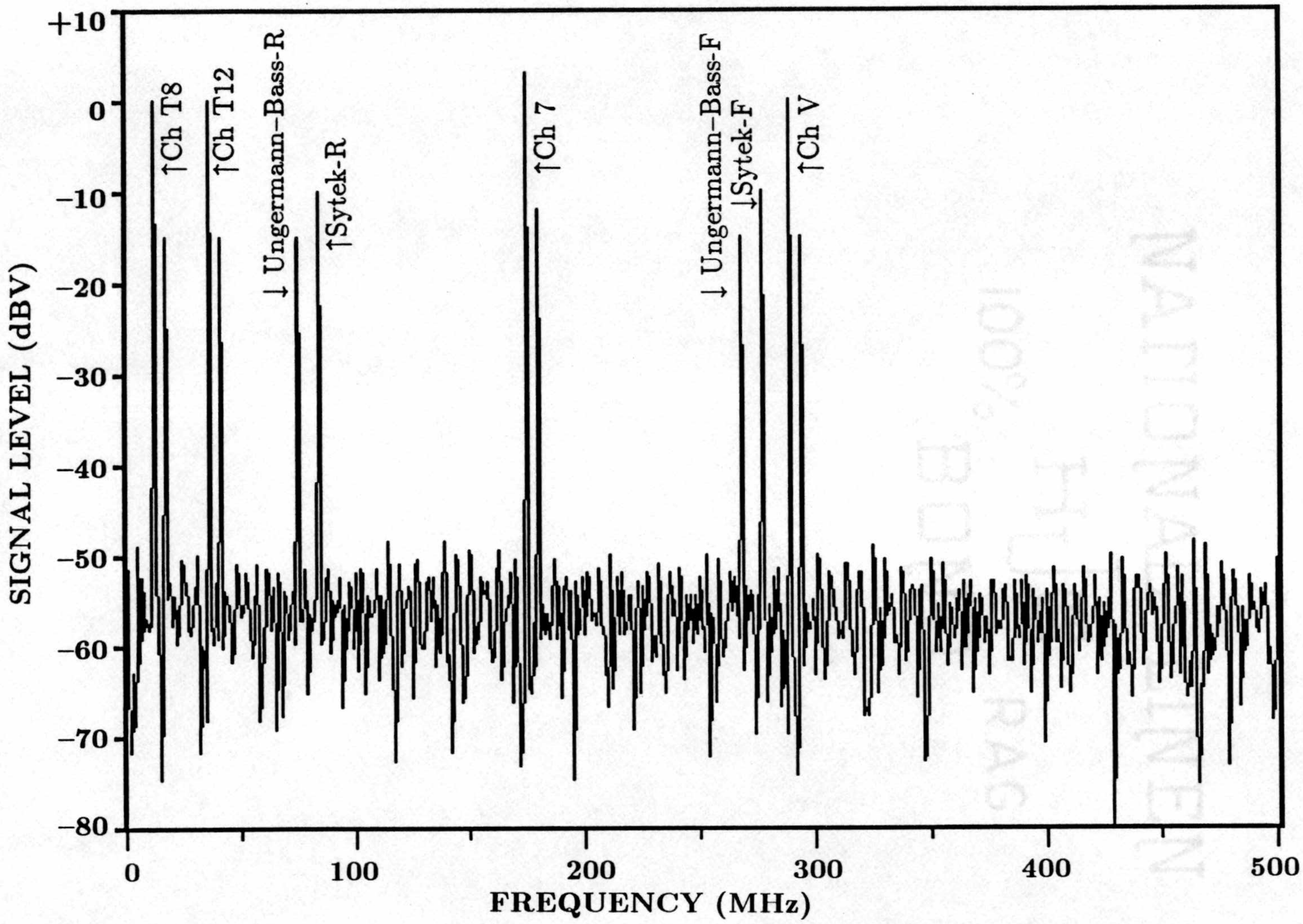

Figure 2.8. Spectrum of a broadband cable with 3-dB compression distortion on one channel.

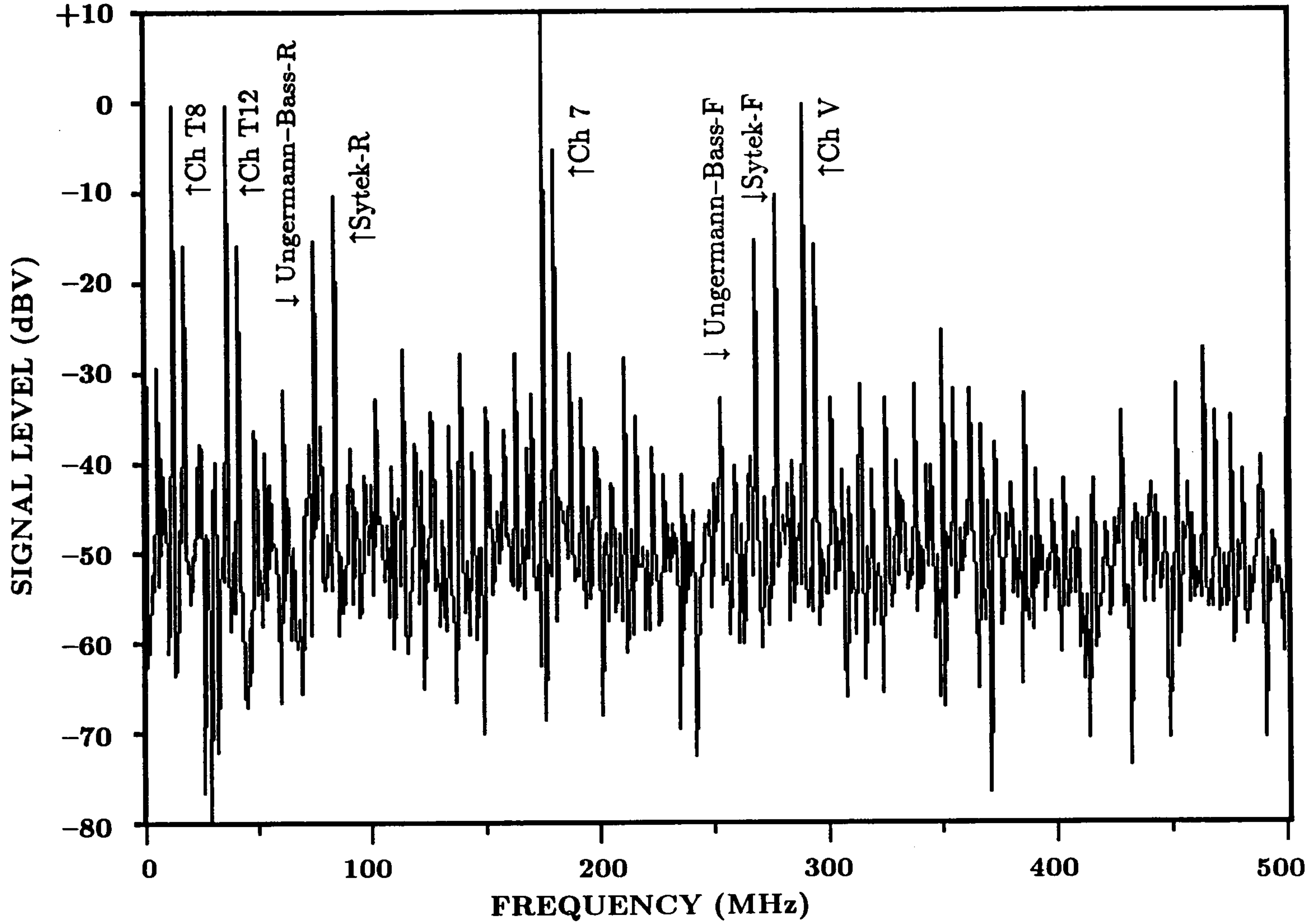

Figure 2.9. Spectrum of a broadband cable with 10-dB compression distortion on one channel.

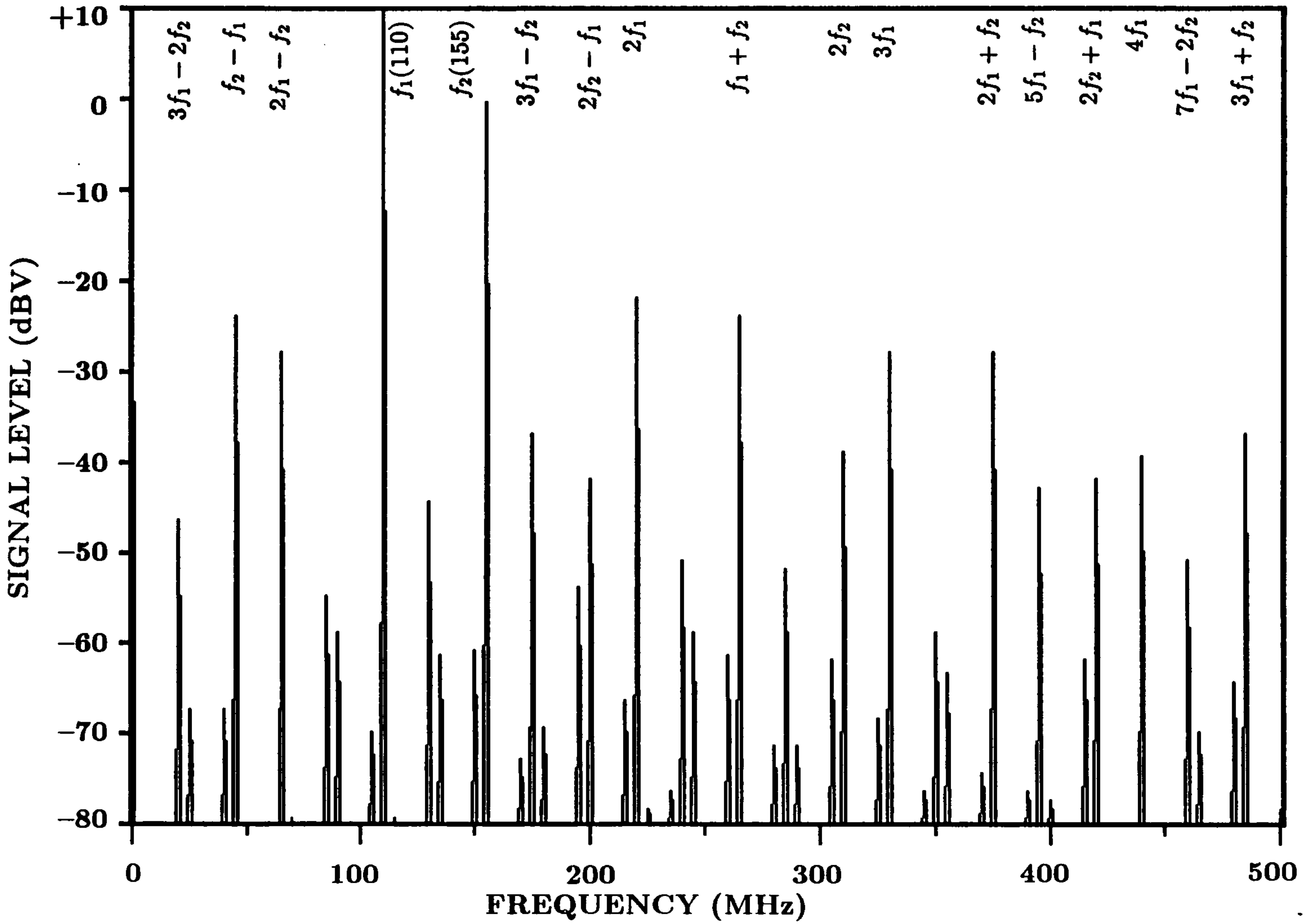

Figure 2.10. Spectrum of a two-tone intermodulation model with 10-dB compression distortion on one tone.

difference, and the third- and fifth-order results that have f_1 as the higher order. The same nonlinearity model was applied with f_1 and f_2 increasing at an equal rate. That spectrum had the second-order products above third-order products, with the third-order products more balanced than in Figure 2.10. Analyses of numerous spectra revealed an important point: the level of a particular intermodulation product is dependent upon both the nonlinearity and the amplitude relationships of the carriers. (Models were created that eliminated even-order distortion products, and one model effectively suppressed the fifth harmonic of an otherwise efficient harmonic generator.) Thus any given model serves only to demonstrate what is possible and does not guarantee that a particular distortion product will dominate. Likewise the broadband system operator cannot guarantee that a particular distortion product will not occur during a failure of the system.

An example of clipping is shown in the spectrum of Figure 2.11. This model has a composite waveform with all carriers increased 3 dB above the limiting threshold. Such a nonlinearity can occur when bias levels change in a faulty amplifier. Again, the nonlinear contributions from 12 carriers generate a spectrum with numerous terms, and the entire noise floor is raised by distortion products. Figure 2.12 shows the same distortion model with only two carriers. Analyzing the noise floor reveals that a rich spectrum is developing, even though only two carriers are involved. It is obvious that clipping distortion provides a hard nonlinearity and should be avoided in broadband equipment.

The final distortion model is rectification. This nonlinearity can occur when a cable connection corrodes from exposure to the weather. As illustrated in Figure 2.13, primary distortion products are approximately 35 dB below peak carrier levels. The magnitude of the distortion products depends upon both the

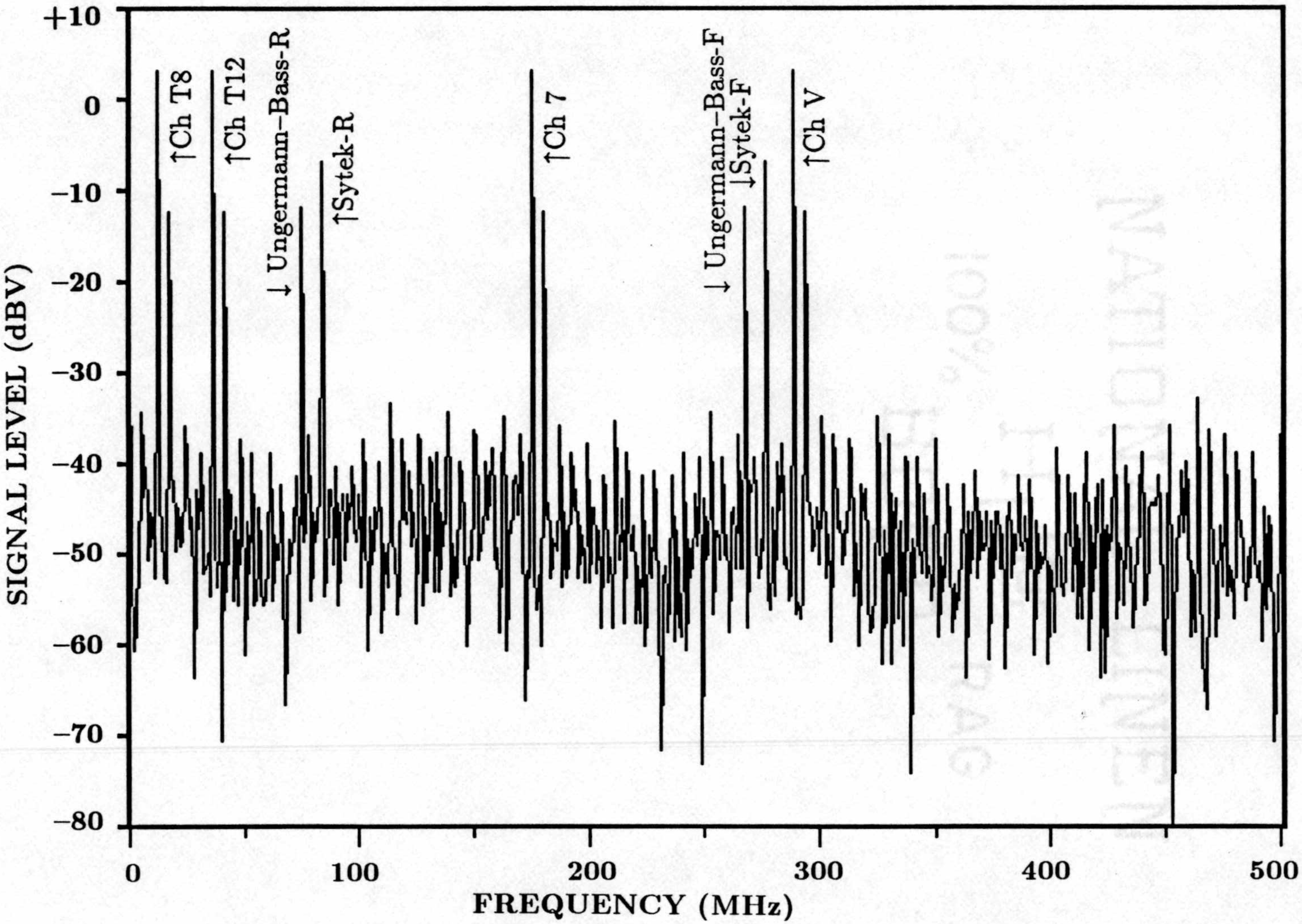

Figure 2.11. Spectrum of a broadband cable with 3-dB clipping distortion on all channels.

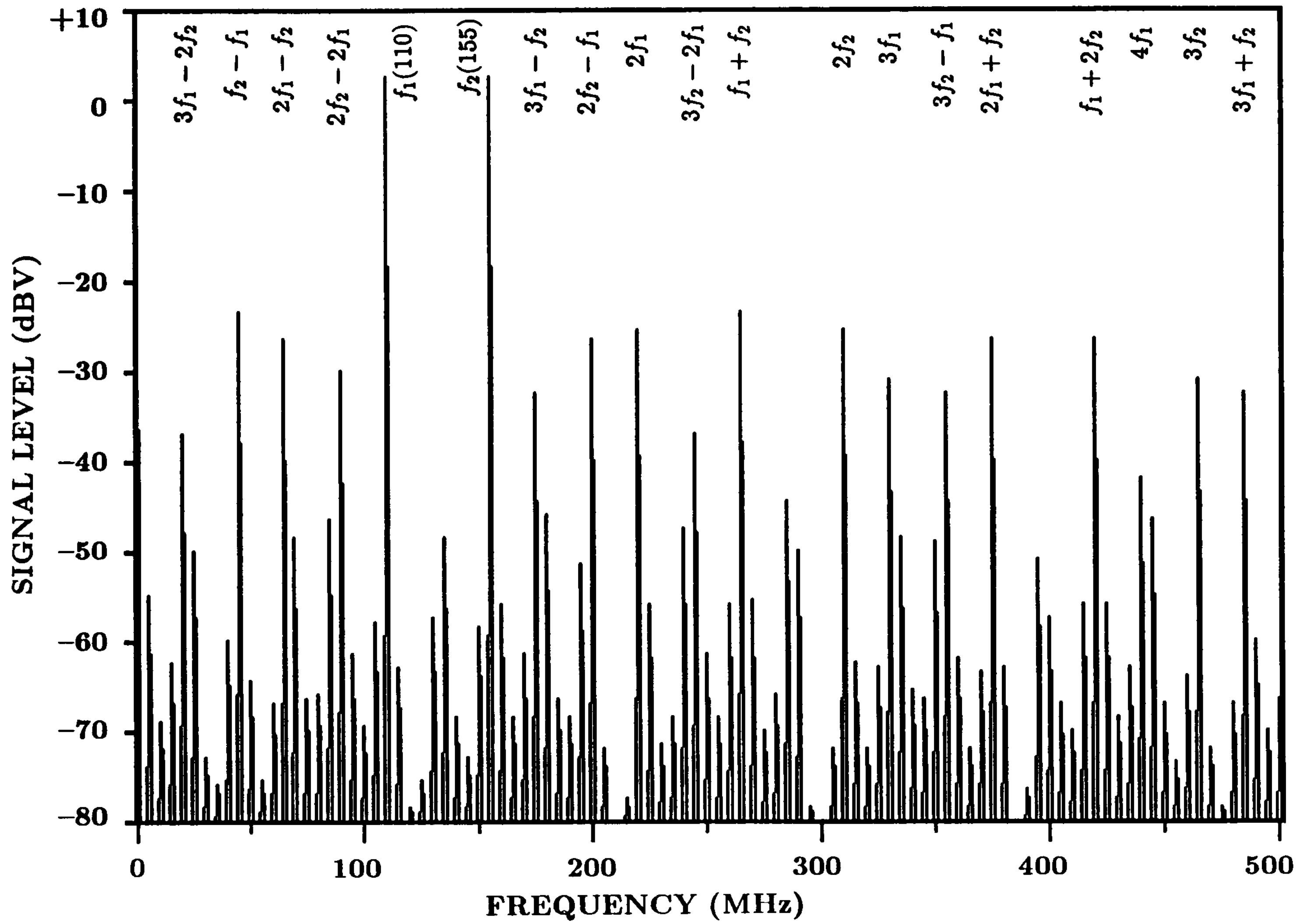

Figure 2.12. Spectrum of a two-tone intermodulation model with 3-dB clipping distortion on both tones.

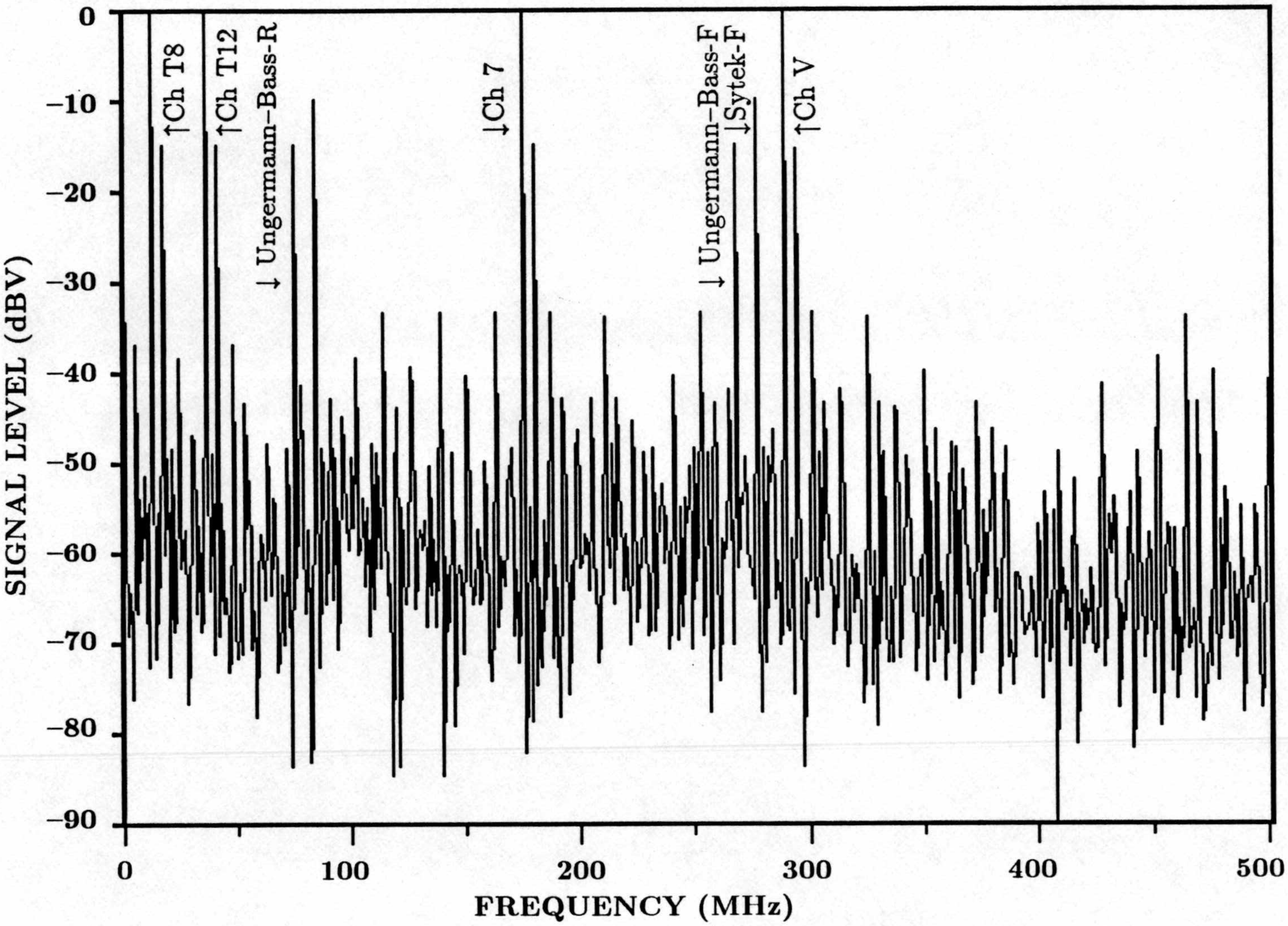

Figure 2.13. Spectrum of a broadband cable with rectification distortion.

characteristics of the rectifier junction and the levels of each carrier. A spectrum of a two-tone model is shown in Figure 2.14. Again $f_2 \pm f_1$ products are strongest. Other levels generally decrease with increasing order, but the nonlinearity can cause pertubations to this rule. For example, the level of $4f_2 - 3f_1$, a seventh-order product, is equal to $2f_2 - 2f_1$, a fourth-order product. Additional insight to dependency on the nonlinear function can be gained by comparing Figures 2.12 and 2.14. In Figure 2.12 the third harmonics are 35 dB below the peak carrier levels while in Figure 2.14 the third harmonics are down by 70 dB. Careful comparison reveals equally interesting differences.

A thorough analysis of the frequency separation layer has established several points. First, broadband cable systems are not linear, and various failure and degradation modes produce spectra with different intermodulation products. These nonlinearity characteristics exist, despite claims by some cable operators that their systems are linear and will provide sufficient data isolation in the frequency layer. Secondly, the variability of the intermodulation products impairs the ability to automatically monitor the broadband for nonlinear distortions that would bypass the frequency separation layer.

Modem Effects on Frequency Separation

While not technically a portion of the broadband cable network, the receivers must be considered in a frequency isolation analysis. Receiver front-end amplifiers are high-gain, low-power devices and are subject to overload. Operation of the receiver in a nonlinear mode will produce intermodulation mixing with the characteristics described in the two previous sections. Intermodulation created within the receiver is not detectable by monitoring the broadband cable system.

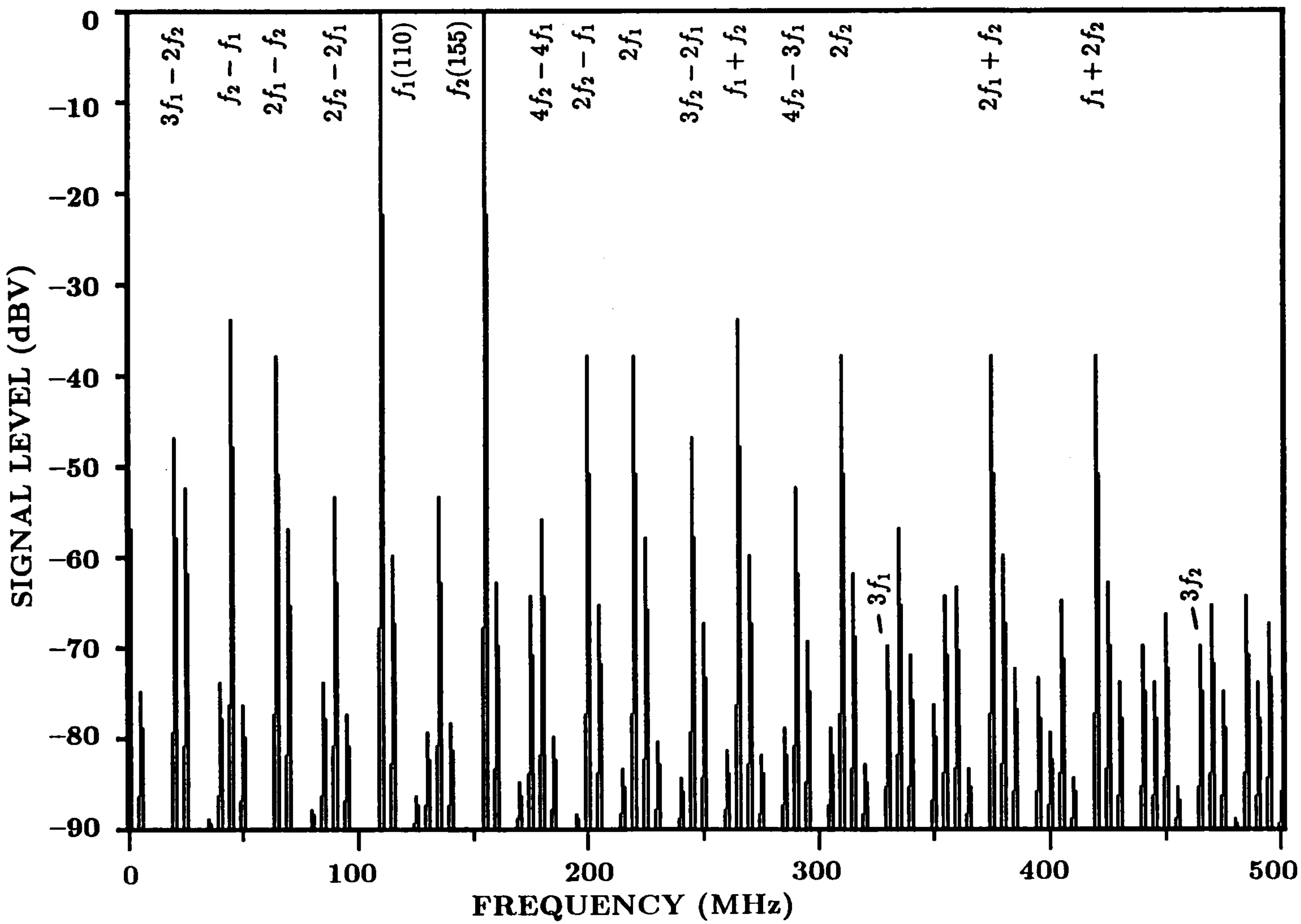

Figure 2.14. Spectrum of a two-tone intermodulation model with rectification distortion.

Other modem and translator specifications have secondary effects on the frequency isolation layer. Extreme frequency instability of a transmitter can place an RF signal, at full power, onto an adjacent channel. Such occurrence is unlikely, but it represents the ultimate breakdown of the frequency separation layer. Out-of-band and spurious emissions from a transmitter can fall into the receive bandwidth of another network. Sufficiently suppressed emissions pose no problem, but if these levels are high, they can produce the same effect as intermodulation.

The receiver specifications of interest are sensitivity and input level. More sensitive receivers respond to lower levels of intermodulation products or out-of-band emissions. Receiver sensitivity will directly influence the margin between normal operating levels and the threshold where an intermodulation product can be received. Sensitive receivers allow the network to remain operational over a wider span of conditions, increasing the network availability during malfunctions. However, a negative aspect arises in that malfunctions are likely to increase intermodulation and that sensitive receivers exhibit a higher probability of responding to these intermodulation products, thus eliminating the frequency separation layer.

Translator specifications are also important to the frequency isolation layer. Bandwidth, frequency stability, and spurious emissions of the translator have effects similar to those described for the transmitters. A parameter unique to the translator specifications is third-order intermodulation distortion. The frequency translation is performed by a heterodyning of the reverse frequencies with a local oscillator. The heterodyning intentionally produces a mixing product at the summation of the local oscillator frequency and the signal frequency. Because the translator is a nonlinear device, operation outside its specified parameters can generate other intermodulation products as calculated earlier.

The intent of mentioning these effects is not to discredit the frequency isolation layer. The layer does exist and is generally effective in segregating the different signals, however care must be taken to ensure that it remains intact. When isolation of data is of utmost importance, other levels of isolation must exist.

RF Bandwidth and Modulation

Bandwidth and modulation are associated with the transmitter and receiver sections of the modem. The original study treated these as one layer of isolation in the RF portion of the modem.[9] The development that follows shows an interrelation, but ultimately reveals an independence.

A strict interpretation of the analysis places bandwidth and modulation into two independent layers, which makes five layers of isolation. Counting the extra layer strengthens the basis for claiming isolation; however it was decided to leave RF bandwidth and modulation as one layer for the purpose of maintaining consistency with previous literature that presented a four-layer concept.[9,10,11,12]

Bandwidth Characteristics of the Two Modems

Bandwidth requirements for the Sytek and Ungermann–Bass modems are quite different, a characteristic that contributes to a second layer of isolation. The Ungermann–Bass modem is configured to emulate the IEEE 802.3 standard.[13] The modem uses a broadband carrier sense multiple access/collision detection (CSMA/CD) system with an instantaneous data rate of 5 Mbps.

The spectral envelope of the Ungermann–Bass signal occupies a full 6-MHz television channel. The RF carrier is centered in the 6-MHz channel and produces a cosine-shaped frequency spectrum when modulated by an isolated maximum-amplitude pulse at the output of the signal coder. The shape of the spectrum is governed by:

$$|G(f)| = 2T\cos(\pi fT), \qquad |f| < 2T$$

$$= 0, \qquad |f| > 2T$$

where $\frac{1}{T}$ denotes the data signaling rate. Maxima occur at the channel midpoint, with zeros at ±2.5 MHz from that midpoint.[14]

The Sytek modem, by contrast, is intended to serve lower data rate users, and the reduced throughput allows channel spacings at 300 kHz with 20 subchannels contained in a 6-MHz television channel. Like the Ungermann–Bass modem, the Sytek modem uses CSMA/CD, but Sytek places the modem carrier in the center of the 300-kHz subchannel. Modulated output of the transmitter is required to be 40 dB (or greater) below the carrier when measured at ±150 kHz from the center frequency.[14]

The Sytek modems are spaced on 300-kHz centers, and the usable bandwidth of the Sytek receiver is approximately 300 kHz. A Sytek modem that is receiving an Ungermann–Bass signal only reacts to a 300-kHz slice of the 6-MHz spectrum. The bandwidth ratio is 1:20, but the amount of instantaneous spectral energy depends upon the portion of the Ungermann–Bass band that the Sytek is receiving.

The primary factor causing the wide Ungermann–Bass spectrum is the 5 Mbps data rate. Although some bandwidth reduction is obtained by processing (discussed under modulation), the width of the Ungermann–Bass data pulses is considerably smaller than the Sytek data pulses. Pulse width is the reciprocal of frequency, so the narrower pulses result in a wider spectrum for the Ungermann–Bass modem. The reduced bandwidth of the Sytek modem does not pass the highest frequency components of the Ungermann–Bass spectrum, and sharp transitions are removed from the data stream. The smoothing of these data transitions causes the received pulses to spread in time, with each symbol spilling into the time interval of the adjacent symbol. This effect, known as intersymbol interference (ISI), reduces the ability of a receiver to properly decode the state of a symbol.[15] For the case where the Sytek modem receives the Ungermann–Bass signal, the receiver bandwidth is approximately 1/20th of the transmitted bandwidth, and ISI is severe enough to leave the recovered signal useless.

A computer model was developed to analyze the effects of bandwidth limiting an Ungermann–Bass type signal. The model applies progressively narrower filters to the frequency-domain representation of a duobinary pulse stream and plots the time-domain result. A listing for the program is included in the Appendix.

Figure 2.15 illustrates the effect of bandwidth limiting on the digital signal. The pulse stream in Figure 2.15(a) is a representative duobinary signal. The leading edge contains short alternating bipolar transitions followed by a series of short unipolar pulses. The next several transitions interleave long and short pulses. Finally, there is one long positive and one long negative pulse.

Figure 2.15(b) shows the recovered duobinary stream after a sinusoidal filter is applied. A single pulse is used to determine the filter cutoff frequency. The shortest duration pulse in the stream will exhibit the highest frequency for the first null in the spectrum, and this frequency is chosen as the cutoff for the filter.

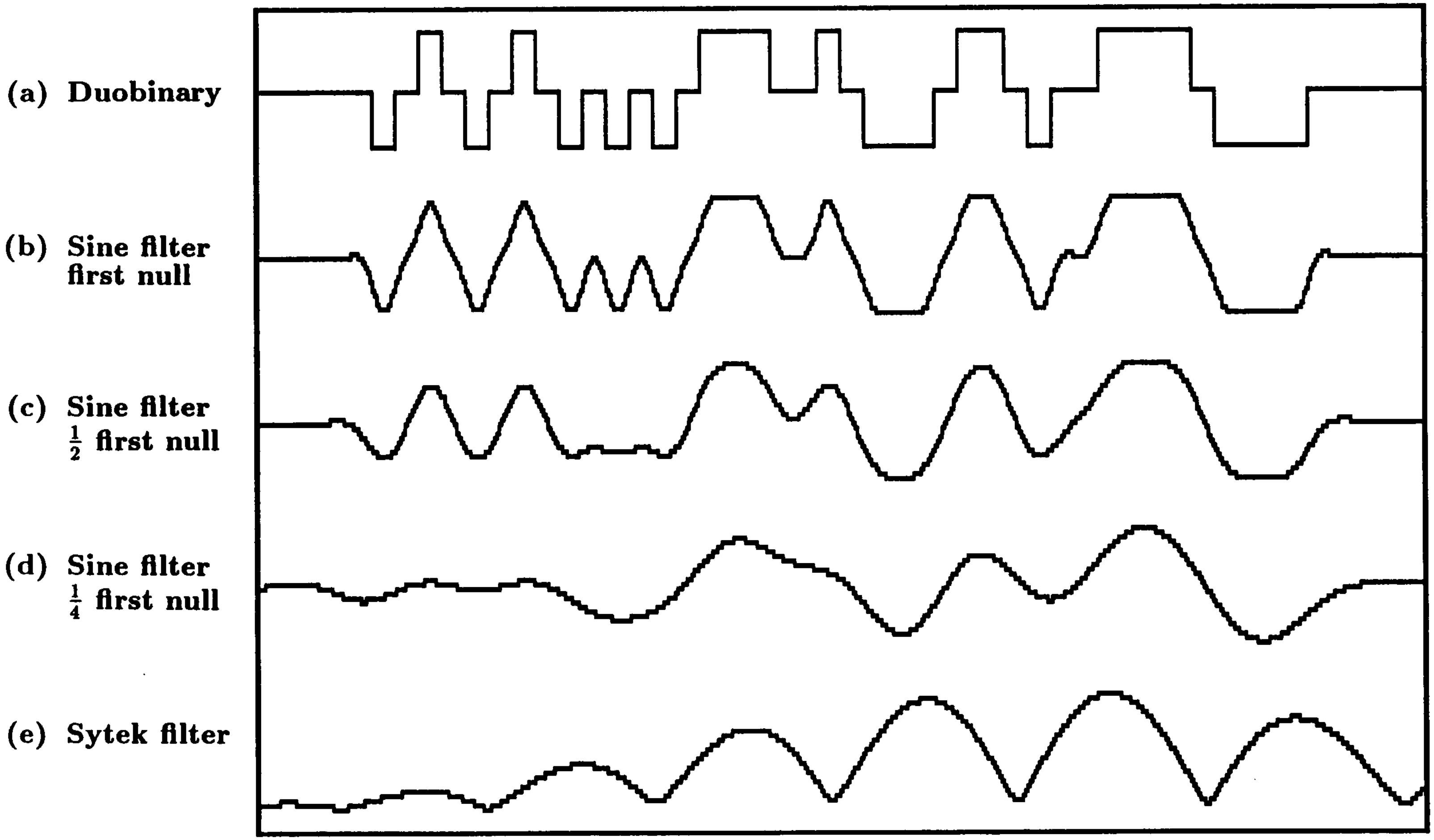

Figure 2.15. Effects of bandpass limiting a duobinary digital signal.

The resulting filter bandwidth is the minimum that can be applied without losing digital information. A sinusoidal filter distribution is applied between the nulls to reduce overshoot and ringing at the data pulse transitions. Both first-null cutoff and sinusoidal filtering are used in the Ungermann–Bass transmitter, and the waveform of Figure 2.15(b) is characteristic of a properly received Ungermann–Bass data stream. It should be noted that all transitions are accurate but the narrower pulses are peaked because of the limited bandwidth.

Intersymbol interference is evident in Figure 2.15(c) when a sinusoidal filter is applied with cutoff at half the frequency of the first null. The short unipolar pulses are lost, and the wider pulses, representing lower frequencies, are distorted. A more severe example of ISI is shown in Figure 2.15(d) where a sinusoidal filter with cutoff at a quarter of the first null frequency has been applied. The trends of the waveform track the longer pulses, but short transitions are lost.

A model of the Sytek receiver passband is next applied. The Sytek receiver exhibits a 3-dB passband of 180 kHz, with the response down by 10 dB at 250 kHz and 50 dB at 450 kHz. Figure 2.15(e) shows the waveform of the digital data when the Sytek receiver model is applied to the center of the Ungermann–Bass spectrum. Because the Sytek filter response is both narrow and sharp when compared to the Ungermann–Bass spectrum, the recovered waveform shows characteristic sidebands of the $\frac{\sin x}{x}$ function that results from a square-pulse filter. If a threshold comparator is applied to the waveform of Figure 2.15(e), the resulting digital output will not resemble the original data stream.

The next computer model passes the duobinary waveform through a sinusoidal first-null filter to simulate the Ungermann–Bass spectrum before applying the Sytek receiver filter. The center frequency of the Sytek filter is varied to demonstrate that the subchannel on which the Sytek is operating affects the recovered waveform. Figure 2.16(a) gives the duobinary reference signal, and Figure 2.16(b) shows the recovered waveform when the Sytek filter is centered on the lower edge of the Ungermann–Bass spectrum. Response when operating on Sytek subchannel 9 is given in Figure 2.16(c). The waveform in Figure 2.16(d) represents Sytek subchannel 12, and Figure 2.16(e) shows the recovered waveform when operating on Sytek subchannel 16, one-half subchannel above the center of the Ungermann–Bass band.

The waveforms of Figure 2.16(b)–2.16(e) demonstrate that the output is dependent on the portion of the Ungermann–Bass spectrum that is within the Sytek receiver passband. Given these conditions, the recovered waveform is more a function of perturbations from the narrow filter than a function of the data.

Spectral bandwidth differences between the two types of modems are sufficient to provide isolation of the two modem networks. When the wide Ungermann–Bass signals are imposed on the Sytek, the spectrum is frequency limited by the filters of the Sytek receiver. This results in severe distortion of the pulses in the time domain, making data recovery by the Sytek discriminator impossible.

<u>Modulation Characteristics of the Modems</u>

The Ungermann–Bass modem, with the wide spectral bandwidth described in the previous section, has a 5 Mbps data rate at the broadband interface. To achieve this data rate within a 5 MHz power spectrum, the Ungermann–Bass modem uses a duobinary AM/PSK modulation. The characteristics of this combination will be analyzed in parts.

The duobinary waveform has the characteristic of representing data symbols by positive pulse levels, negative pulse levels, and the lack of a pulse. A model

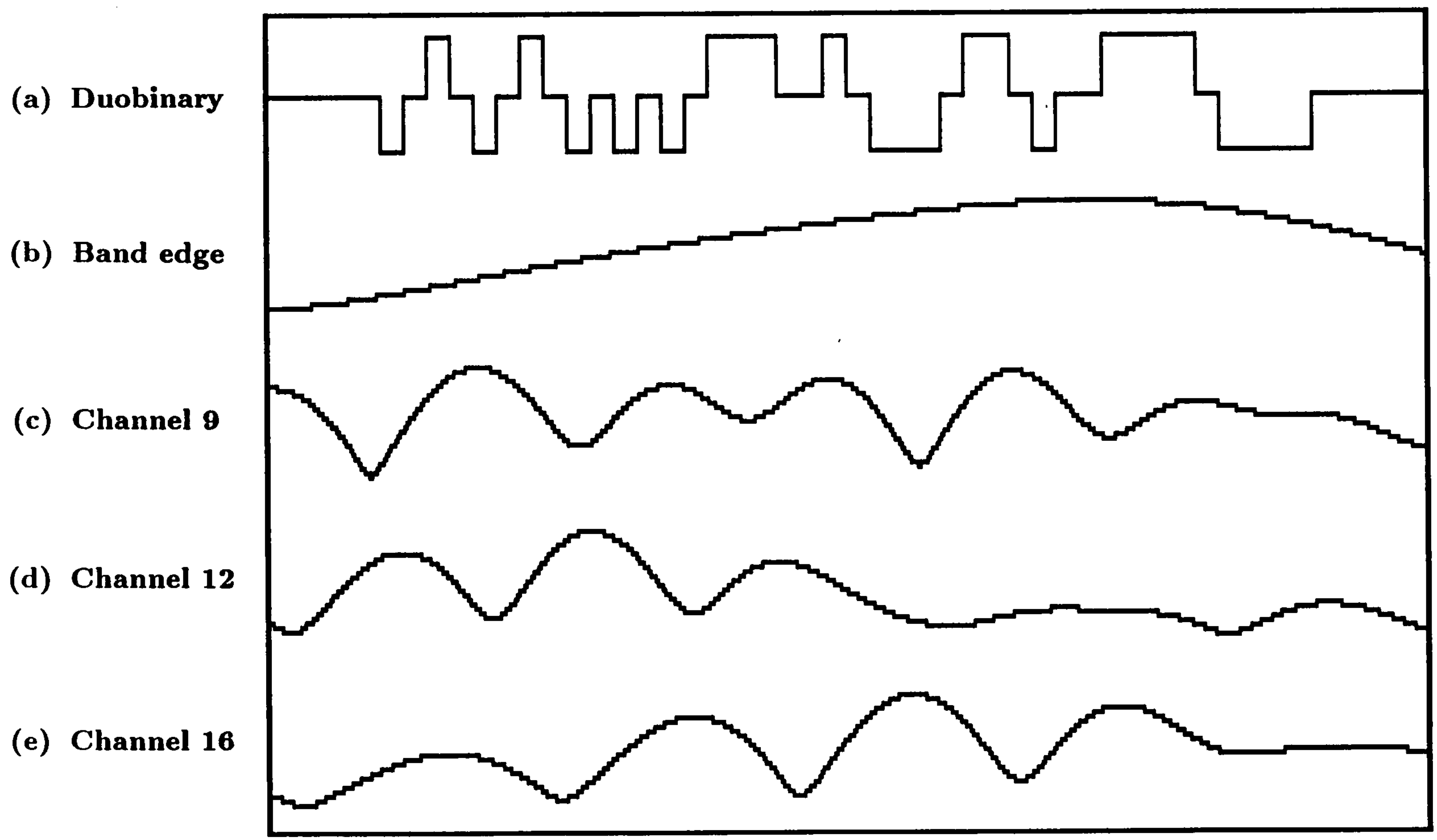

Figure 2.16. Effects of the Sytek IF receiver filter on an incoming Ungermann–Bass signal.

for a duobinary encoder is shown in Figure 2.17.[15] The effect of the encoder is to produce a data stream with each state dependent not only on the present data bit but on the previous data bit.

As an example, consider the bit sequence **0011110110000111001O**. In Figure 2.18, the first entry for the encoded sequence is indeterminate because the previous bit is unknown. The second entry sums two **0**s to give an output of $-\mathbf{A}$. The next **1** sums with the previous **0** to give an encoded **0**. The repeated **1**s sum to create **A**s. Further analysis of the encoded waveform shows that repeated **1**s give **A**, repeated **0**s give $-\mathbf{A}$, and alternating **0**s and **1**s give **0**s.

The receiver decoding algorithm produces a **1** if the input is an **A** and a **0** if the input is a $-\mathbf{A}$. If the input is a **0**, then the decoded output is a **1** if the previous bit was a **0**, and the decoded output is a **0** if the previous bit was a **1**.

Figure 2.18 also shows the binary and encoded waveforms for the example duobinary signal. The duobinary waveform has the advantage that an encoded symbol exhibits twice the basic pulse width of a given unencoded symbol. Because of the $\frac{1}{T}$ relationship between the time and frequency domains, an encoded sequence can be transmitted with half the required bandwidth of an unencoded sequence.

Analysis of the encoded sequence provides a strong argument for isolation. While a high-level pulse indicates **1**s and a low-level pulse indicates **0**s, there is an absence of pulses which can indicate either a **1** or a **0**, depending on the previous bit. A digital receiver that is not designed to decode duobinary signals will either ignore or incorrectly interpret the data represented by the absent pulses.

The Ungermann–Bass modem uses the duobinary waveform to modulate a carrier as AM/PSK. The phase of the carrier is determined by either the high or the low level of the waveform. Amplitude modulation is obtained by switching

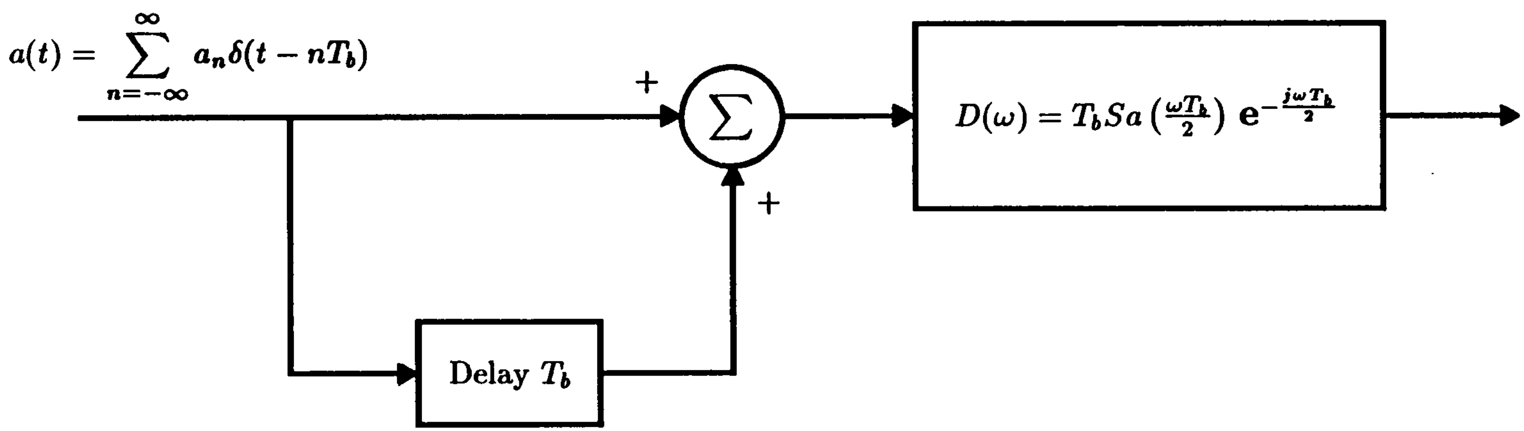

Figure 2.17. Block diagram of a duobinary encoder model.

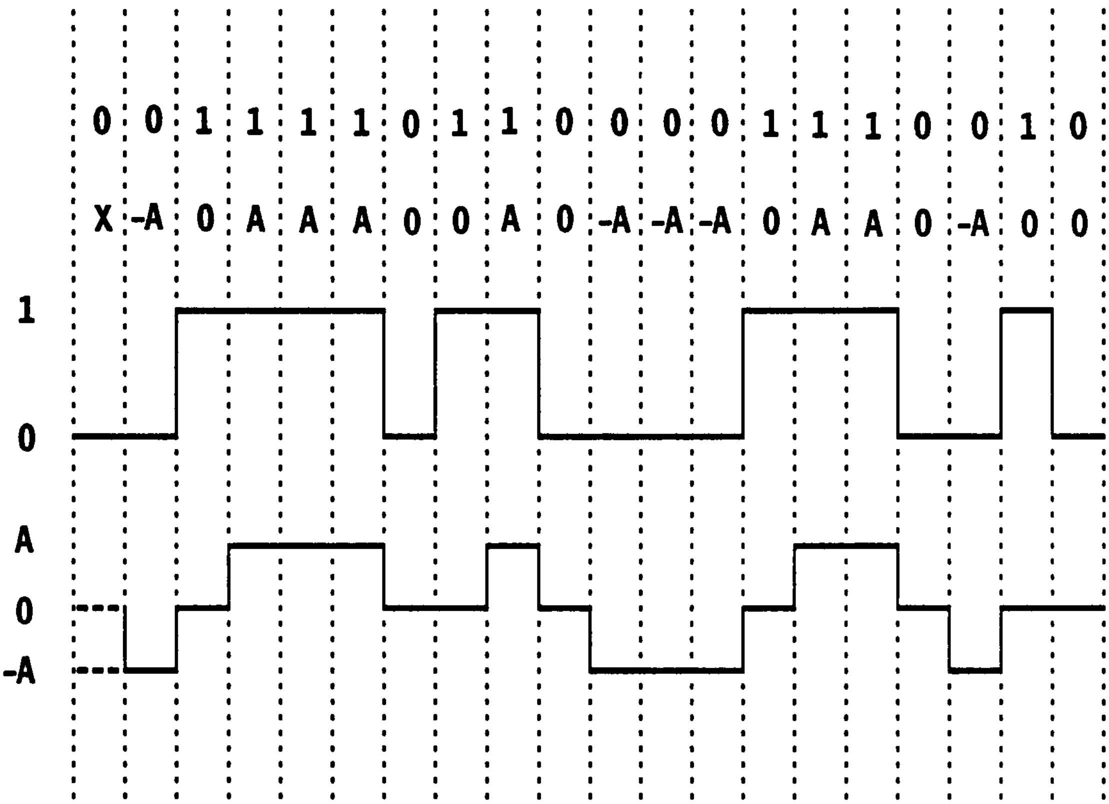

Figure 2.18. Example bit sequence for a duobinary signal.

the carrier off during the zero level of the duobinary waveform. The net result from a design standpoint is an increase in spectral efficiency of the Ungermann–Bass modem. The isolation benefit comes from both the data encoding into duobinary and the modulation as AM/PSK.

The Sytek modem has a data rate of 128 kbps at the broadband interface. This lower data rate reduces the requirement for stringent bandwidth conservation. As a result, Sytek chose a phase-continuous FSK with a deviation of ±29 kHz. The received signal for the FSK system is processed through a limiting amplifier to remove fluctuations in amplitude. The demodulator senses whether the received carrier frequency is above or below the center frequency, decoding this relationship into either **1**s or **0**s. Such an FSK system exhibits excellent noise rejection characteristics.

When the duobinary AM/PSK signal from the Ungermann–Bass is applied to a Sytek FSK receiver, several processes occur. First, the AM portion of the signal is rejected. The Sytek modem, under the CSMA/CD protocol, senses a lack of carrier as meaning that the channel is clear for transmission, and Ungermann–Bass data, represented by the absence of a carrier, are lost to the Sytek receiver.

The second aspect of modulation isolation is derived from the differences in PSK and FSK. Phase modulation of a carrier can be expressed as the integral of the instantaneous carrier frequency, and, in turn, instantaneous carrier frequency can be expressed as the derivative of the carrier phase. For analog sinusoidal modulating functions, the same detector will recover either phase or frequency modulation (with a phase shift).

Square wave modulating functions produce a more diverse result. When a square wave is applied to an FM modulator producing FSK, the integral of the instantaneous carrier frequency produces a triangular phase relationship.

Conversely a PSK signal, because of the derivative operator applied to phase discontinuities, produces sharp impulses of frequency modulation.[16]

Demodulation techniques for FSK and PSK do not possess the similarity of the analog case. The spectrum for a PSK signal is essentially the same as that for a bipolar AM. In the case of the Ungermann–Bass modem with duobinary AM/PSK, the modulation is a three-level AM, with phase discontinuity between the negative data symbols and the positive symbols. Demodulation of PSK or AM/PSK is performed with a single-frequency synchronous detector while FSK synchronous detection requires two reference frequencies for signal recovery.[5]

Certain phase/frequency relations in the Ungermann–Bass AM/PSK signal may produce output from the Sytek FSK detector. The AM/PSK will appear as impulse FSK in the Sytek receiver, but the response will be a more complex function than normally expected. Differences in data timing, pulse width, and bandwidth will affect the impulse FSK characteristics. The modulated signal will more nearly resemble a randomly driven frequency modulator than a coherent data system. Demodulator performance will be unpredictable, and the recovered output will not be in a form that allows the Sytek to decode usable data.

In summary, the bandwidth and modulation layer of isolation is produced by the additive results of several implementation differences. The wider bandwidth of the Ungermann–Bass is distorted when band limited by the Sytek receiver, resulting in intersymbol interference and a smearing of the data. The Ungermann–Bass data are encoded as a duobinary AM/PSK, resulting in lost bits, rejection of the AM portion, and random response to an impulse FSK signal. Demodulator response of the Sytek is more likely governed by patterns in the data stream rather individual bits of data. With these characteristics in mind, the bandwidth and modulation layer forms a strong defense against communications from one modem network being correctly received by the other.

Digital Detection

It can be seen from Figure 2.1 that signals from the Sytek modem receiver are next sent to a serial input/output (SIO) chip, the Zilog Z8442. This SIO is a dual-channel programmable data communications interface with the **A** channel used to interconnect the 128-kbps serial data to the parallel bus structure of a Z80 microprocessor.

A partial block diagram of the receive section is shown in Figure 2.19.[17] Serial data enter the port marked RxDA. After a 1-bit delay, the data are clocked into an 8-bit shift register that performs the serial-to-parallel conversion. The data are checked for various errors, and if acceptable, are sent to a first-in, first-out (FIFO) buffer. When valid data are available, they are sent across the internal data bus to the data I/O buffer. An interrupt is generated for the microprocessor, and data are transferred to the Sytek bus under the control of the microprocessor.

As illustrated in Figure 2.19, error checking is performed on the receive data. The SIO is operating in the asynchronous mode, so cyclic redundancy code (CRC) checking is not performed at the chip level. The asynchronous mode does support data tests for framing errors, overrun errors, and transient spike rejection. The transient rejection circuitry checks the status of the incoming bit stream at one-half of a bit time after a transition to low is detected on the receive data input. If the low level does not persist, as in the case of a transient, the character assembly process is not started.

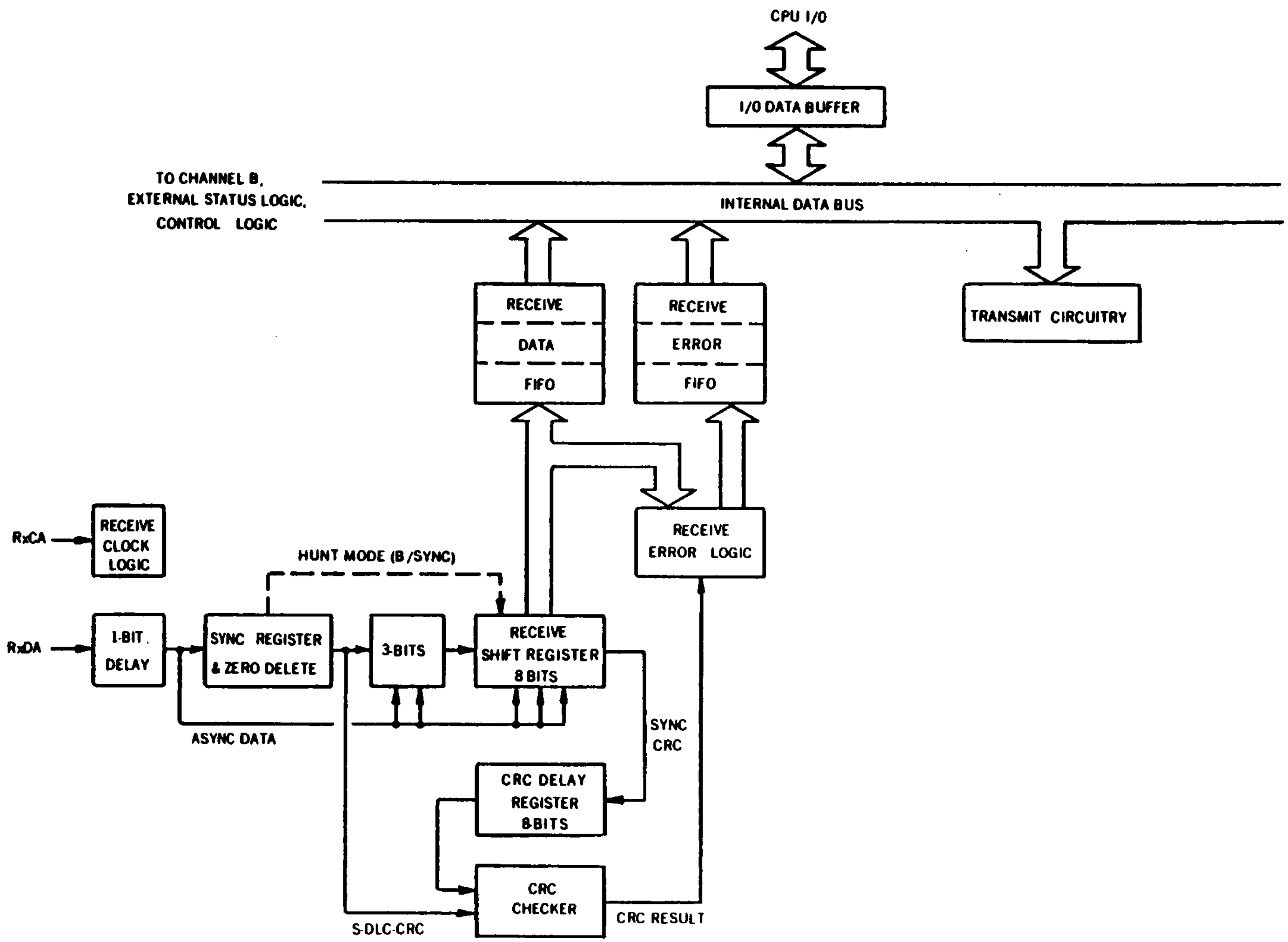

Figure 2.19. Partial block diagram for the Z8442 serial input/output receiver.

When an error is detected from one of the character length tests, an error code is generated and sent to the receive error FIFO. At the appropriate time, the error bytes are transferred across the internal data bus to the I/O data buffer. An interrupt is generated for the microprocessor, and the error codes are transferred to the Sytek data bus under control of the microprocessor. The processor acts on this error to either ignore the data or generate a higher-level error code.

The transient rejection process is of special interest in the analysis of the digital detection isolation layer. As was discussed in the RF bandwidth section, the Sytek serial data rate at the broadband interface is 128 kbps while the Ungermann–Bass data rate is 5 Mbps. Because of the difference in received symbol width, the Ungermann–Bass data pulses are narrower than normally expected by the Sytek system, even after the spreading caused by the limited bandwidth of the Sytek receiver. Timing relationships between data symbols for the two networks also differ. The timing and pulse width inequalities activate the transient rejection circuitry, causing the character assembly process to be aborted.

More significantly, the Ungermann–Bass PSK modulation is detected as impulse FSK by the Sytek receiver. If these impulses are perceived as transient noise, the SIO rejects the data entering the serial input.

The error detection and transient rejection properties of the Sytek SIO interface circuit cause a rejection of data that do not conform to the predetermined timing characteristics for the serial data interface. When this protection is coupled with the pulsewidth, timing, and modulation incompatibilities of the Sytek and Ungermann–Bass networks, a layer of isolation is created between the networks.

Packet Transmission Protocols

The fourth layer of proposed isolation for the two modem networks is provided by the data packet transmission protocols. Because schematics of the Sytek modem are proprietary and thus not available, the point at which the protocol is applied could not be specifically determined. None of the integrated circuit numbers match those of commercial protocol chips. Several programmable array logic devices are inserted in the signal path between the demodulator and the SIO. However, characteristics of the serial signal entering the SIO do not suggest that protocol processing has occurred prior to that point. Based on these observations, it is assumed that the protocol processing is performed by the microprocessor. This method is not particularly efficient, but it is feasible, considering the relatively low 19.2 kbps average data rate and the high 6 MHz microprocessor clock rate.

Network protocols are typically divided into several layers. These layers can include access, presentation, session, transport, network, link, and physical.[18] For purposes of isolation, the protocol as applied to the communications packet structure will be studied. Verification of an isolation layer will be shown by analysis of packet protocol differences.

The frame format for a packet on the Ungermann–Bass system is shown in Figure 2.20. This is the standard Ethernet or IEEE 802.3 format. The packet consists of a preamble of 8 bytes, a destination address of 6 bytes, a source address of 6 bytes, a length designator of 2 bytes, a data packet that can vary from 46 to 1500 bytes, and a frame check sequence of 4 bytes. Adding these fields gives a packet size of 72 bytes minimum and 1526 bytes maximum.[19]

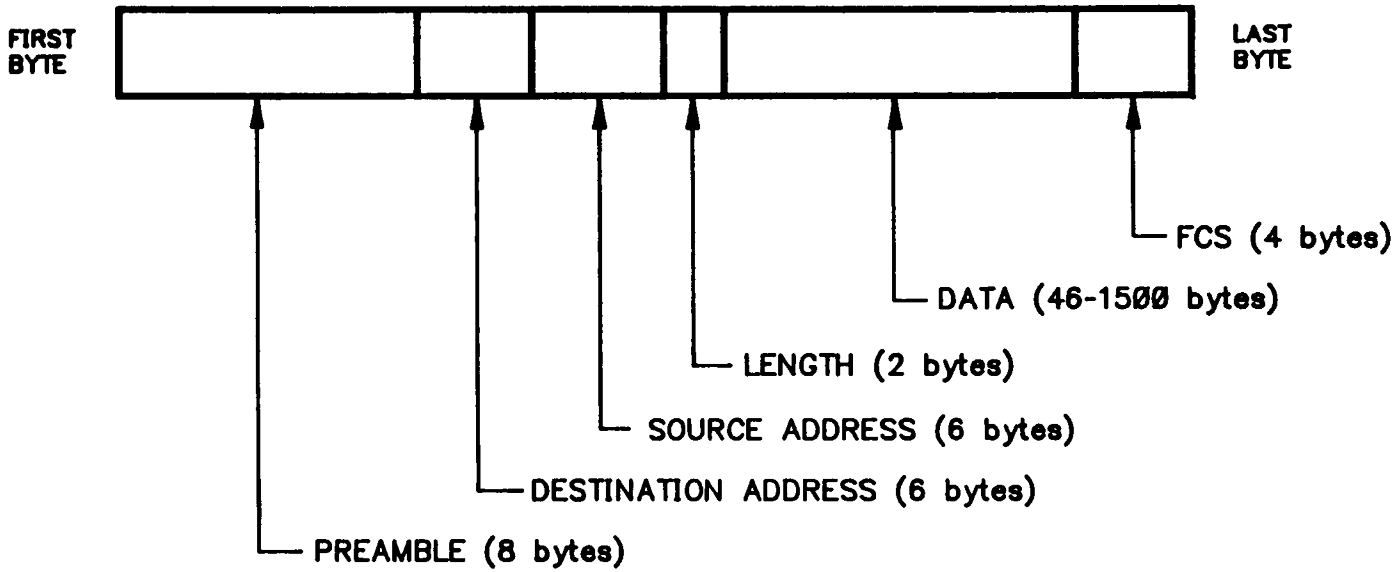

Figure 2.20. Packet protocol frame format for the Ungermann–Bass modem.

The first portion of the packet is the preamble and is equivalent to a synchronization character. The preamble is 64 bits in length, with the first 62 being alternating 1s and 0s and the final two being **11**.

The destination and source addresses are each six bytes in length. Each node has a unique address that is registered according to manufacturer. Portions of the address identify the manufacturer and piece of equipment.

The length field contains two bytes and indicates the number of characters that are in the logical link control (LLC) field. This count includes valid data from the upper level layers and the user data. Pad bytes are not included in the count specified by the length designator.

The data or logical link control field contains the message that is being sent in the overall packet. The data field is required to be a minimum of 46 characters and a maximum of 1500 characters. If the data field is less than 46 bytes, the field is padded to make a total of 48 bytes. In addition to the user data, the LLC field is included in the data area. This field provides space for the upper layer protocol information that is transmitted.

The final field of the packet is the frame check sequence (FCS). The FCS provides a 32-bit CRC check on the fields starting with the source address and continuing through the LLC field.

The frame format for the Sytek protocol is shown in Figure 2.21. The session management protocol has 1 byte for control and 0-64 bytes for user data and/or control. This packet merges into the reliable stream protocol, which adds one additional byte each for send control, receive control, destination connection identifier, send sequence, and receive sequence. These 70 bytes are merged into the packet transfer protocol, which has 2 bytes for destination unit ID, 2 bytes for source unit ID, 1 control byte, and 5 bytes for an optional trailer. The link access

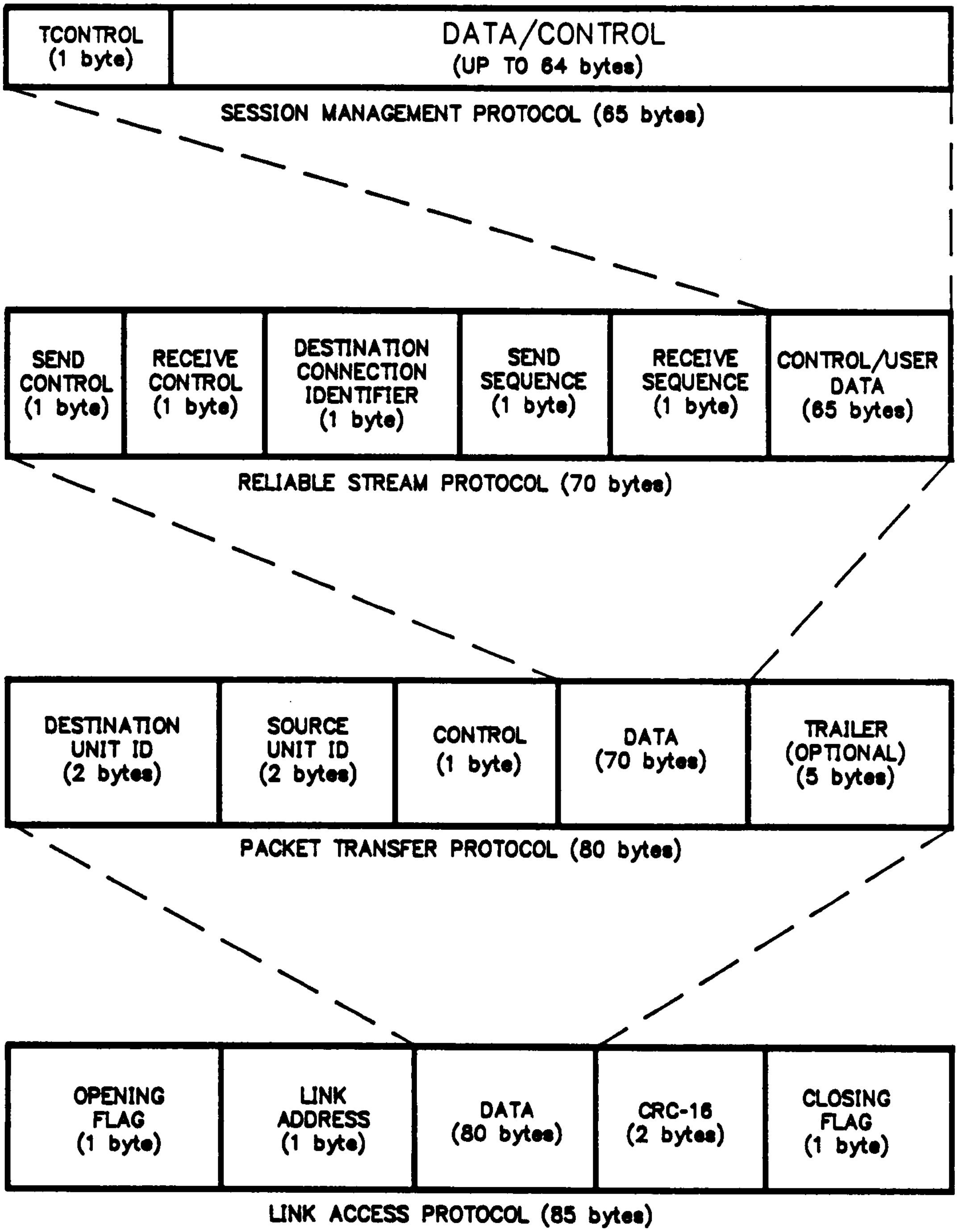

Figure 2.21. Packet protocol frame format for the Sytek modem.

protocol has 1 byte for an opening flag and 1 byte for a link address. The data block can be 16 to 80 bytes depending upon the amount of user data. Finally there are 2 bytes allocated for a 16-bit CRC code and 1 byte for a closing flag. The link access protocol has a minimum packet size of 21 bytes and a maximum packet size of 85 bytes.[20]

The minimum Ungermann–Bass packet length of 72 bytes creates a 13 byte overlap between the minimum Ungermann–Bass and the maximum Sytek packet length. However, the differences in packet size and number of bytes allocated to addresses and data make it unlikely that the Sytek would decode the Ungermann–Bass transmission even if valid bytes were available on the data bus. The 16-bit CRC code of the Sytek provides additional assurance that data, if present, will not be decoded.

Comparison of the protocols completes the theoretical analysis of the four layers of modem isolation. Chapter 3 will present the measured results for each layer.

CHAPTER 3

TEST RESULTS

The test results of the isolation obtained from the mixed-modem technique are presented in this chapter. A description of the broadband network and measurement techniques are presented to establish the conditions under which the tests were made. Results of measurements are presented in the same order as that of the theoretical analysis. Where applicable, comparisons will be made between the theoretical results and the measured data.

Broadband Test Network

A broadband test network was used to determine whether sufficient isolation is obtainable from the mixed-modem technique. The use of an independent network provided the characteristics of an operational broadband system while allowing performance degradations to be introduced without interference to, or disruption of, other broadband operations. The test network was a midsplit, 300-MHz trunk system configured to represent typical Ungermann–Bass Net/One and Sytek LocalNet networks. The test system was configured with two trunk amplifiers, categorizing it as a small network; however, the characteristics of the tests performed minimized the effects of the size restriction.

A greater deviation from normal operating practices was the assignment of the Ungermann–Bass and Sytek modems to the same operating frequency. This technique is not recommended in a networking environment but was necessary as a means of defeating the frequency separation layer of isolation. Placing the modems on the same channel provided maximum RF signal for evaluating the remaining layers.

Testing of the broadband isolation was performed in two phases. The first phase was reported in the original study.[9] The second was conducted as research for this thesis and expanded the measured results in terms of both the number of parameters measured and the duration over which the measurements were performed.

Figure 3.1 shows a block-diagram layout for the original broadband test network. The headend of the system is an Ungermann–Bass model 5517A translator with an offset frequency of 192.25 MHz. The translator input is on cable channel 4A, and the output is on cable channel R. A variable attenuator is inserted at the translator to provide a convenient method of introducing variations in the system gain. This capability allows operation with controlled carrier levels for testing at both low signal-to-noise ratios and high-level overload conditions. The trunk amplifiers are installed with bridging outputs feeding distribution taps. A configuration of this type, typical of networks connecting small office complexes, provides subscriber taps with normal operating levels. A CATV preamplifier is connected to one of the subscriber taps to perform the impedance matching and level adjustment necessary for monitoring the system with an RF spectrum analyzer. The trunk amplifiers, translator, directional coupler taps, and CATV preamplifier are shown in Figure 3.2.

Two Ungermann–Bass network interface unit (NIU) model NIU-180 modems were installed, providing eight RS-232 ports each. A Personal NIU-2361A was installed in an IBM PC/XT as the network controller and traffic monitor. With this internal modem card, the personal computer could monitor information on the communications traffic routed over the Ungermann–Bass portion of the network. The Ungermann–Bass modems and the personal computer network controller are shown in Figure 3.3.

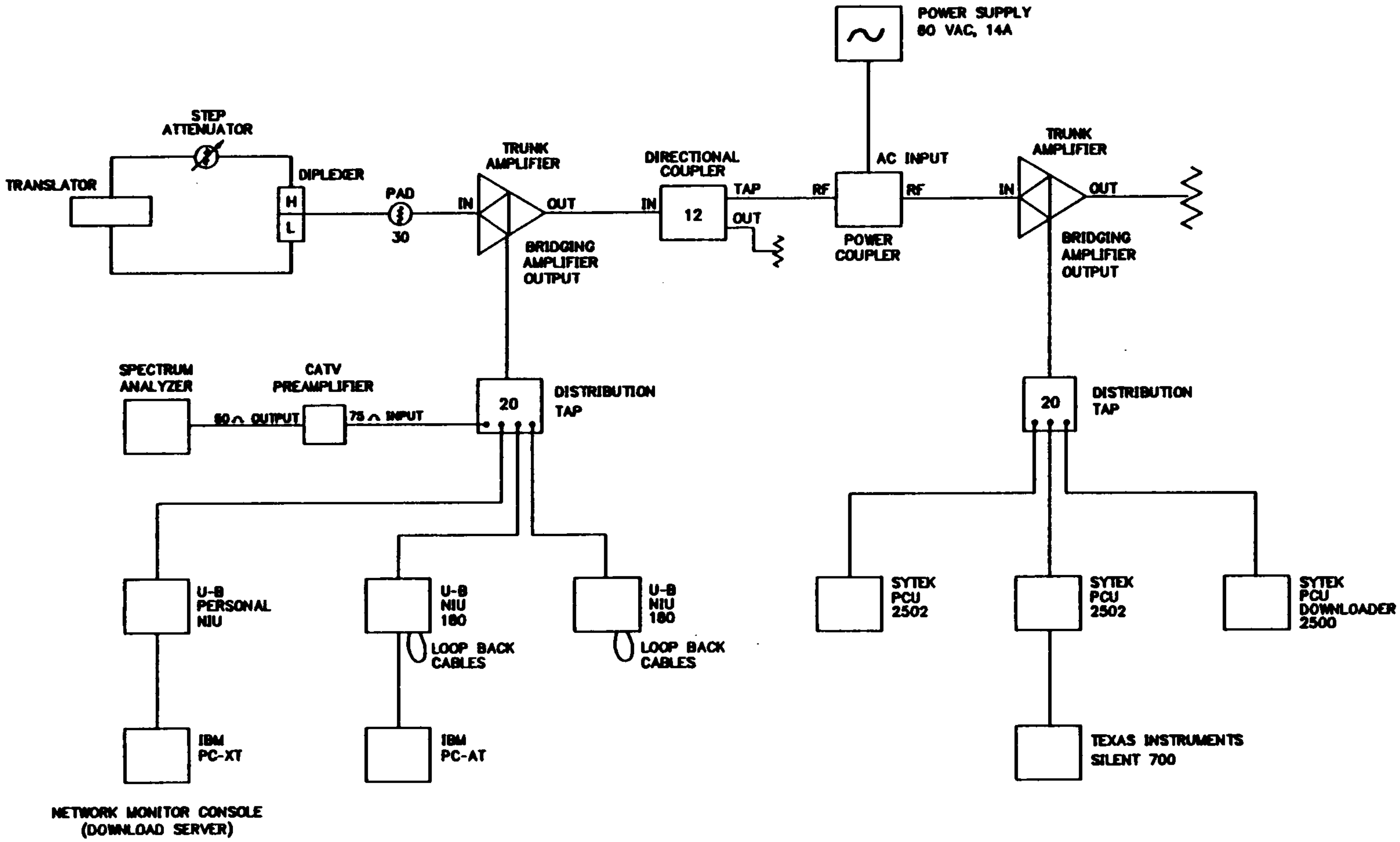

Figure 3.1. Block diagram layout for the broadband test network.

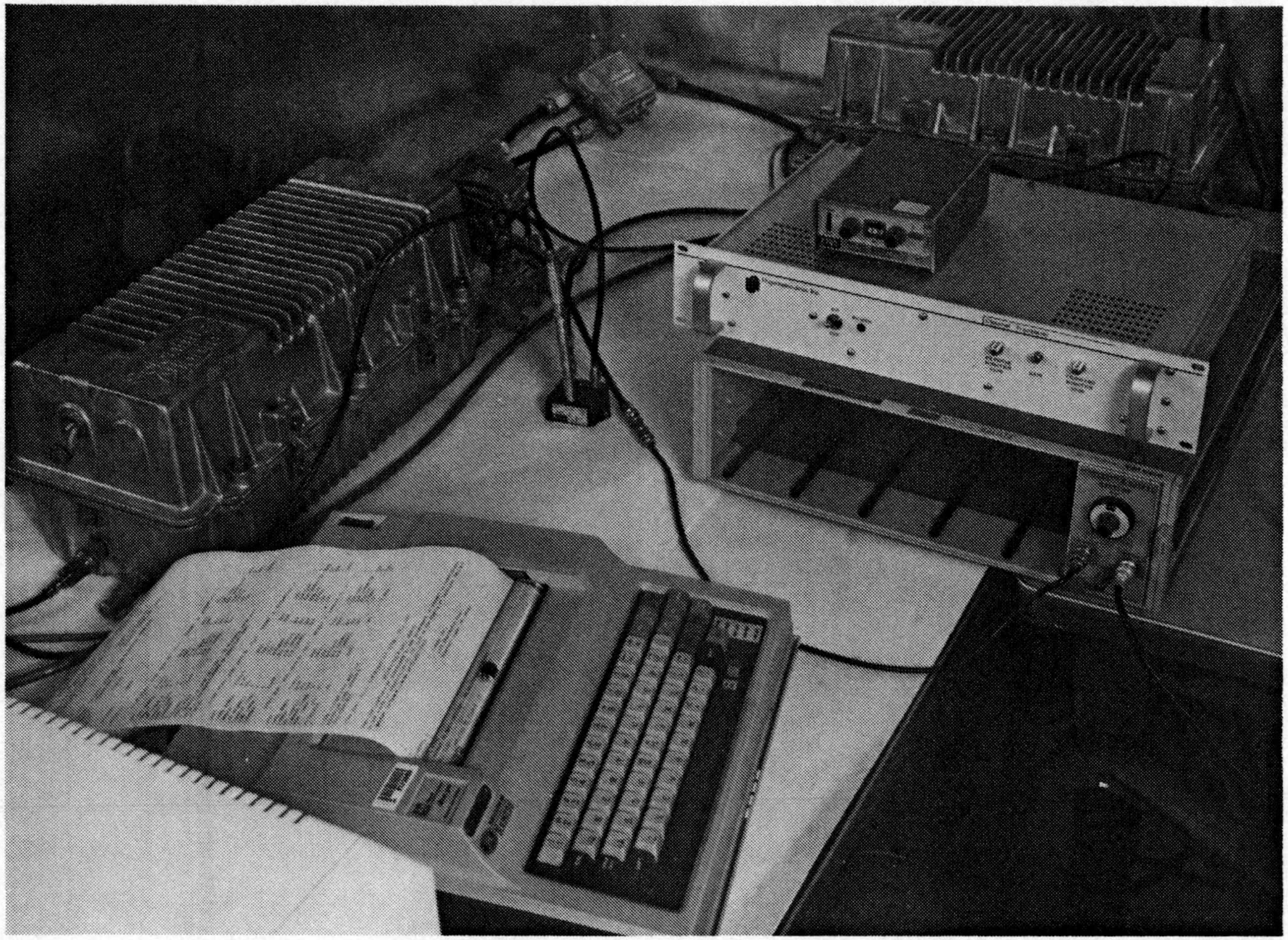

Figure 3.2. The broadband test network and monitoring setup.

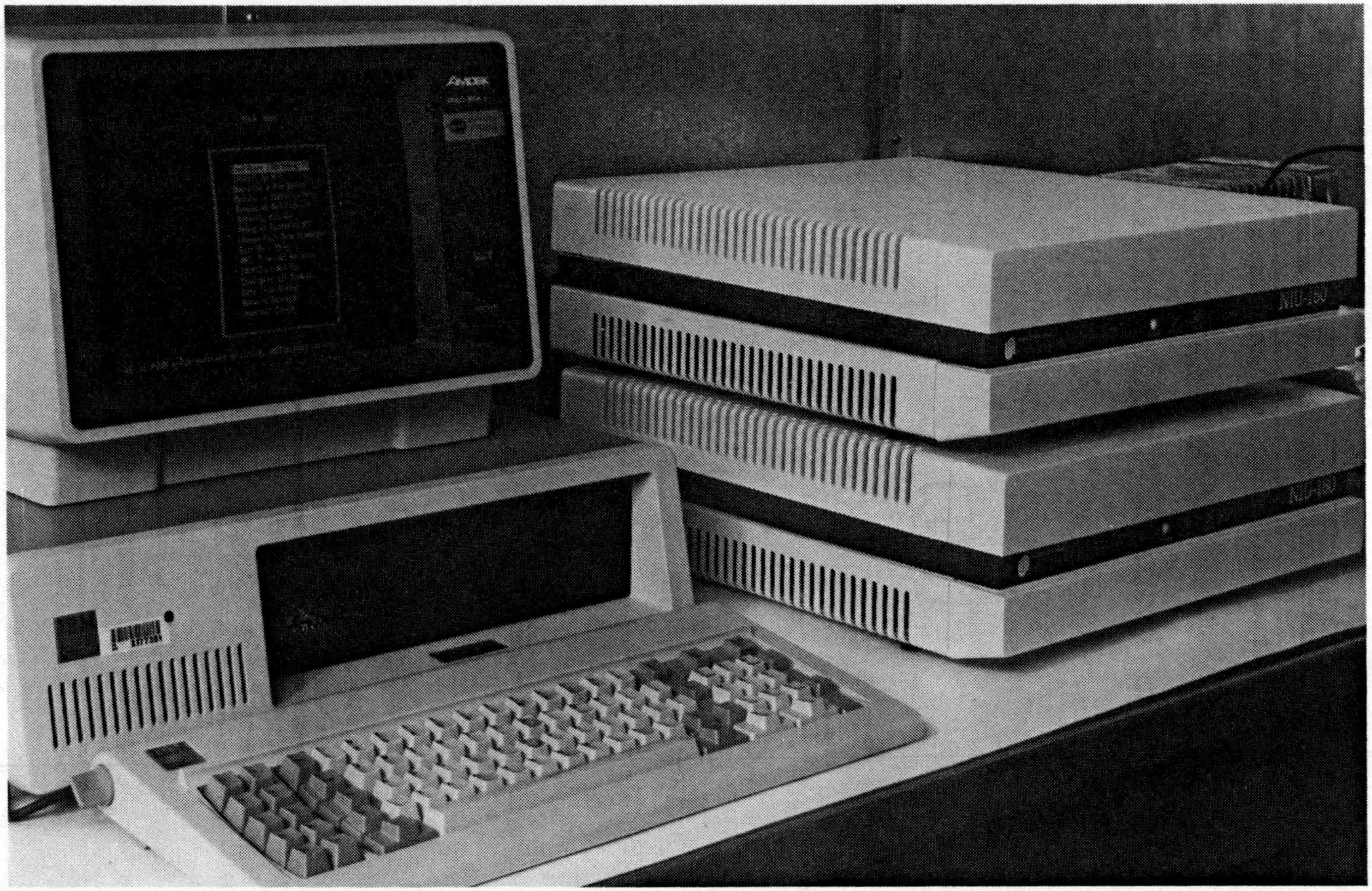

Figure 3.3. The Ungermann–Bass NIUs and network controller.

The Sytek equipment used during the tests included a model 2500 packet communications unit (PCU) downloader and two model 2502 PCU modems. Each modem provides two RS-232 user ports. Figure 3.4 shows a model 2502 modem that is removed from the case for testing. The digital circuit board can be seen on the right, and the receiver board is on the left. The front panels of a model 2502 modem and the model 2500 downloader are visible in the upper right corner of the photograph.

An IBM PC/AT was installed as the data driver for the test setup. The computer was connected to an NIU-180 serial port and served both as a terminal and a data generator. During setup of the modem sessions, the terminal was used to make a network connection to another NIU port. When the connection was established, the called port was linked through a serial cable to another NIU port. The connection from the computer, through the network to that port, was transparent, and the process was repeated until all 16 ports were connected in a "daisy chain" manner. A switched loopback plug was installed on the final port to permit control of data flow in the reverse direction. The interconnection of serial ports expanded the Ungermann–Bass network traffic by providing up to eight network sessions. The additional data flow increased the spectral activity from the Ungermann–Bass modems.

Figure 3.1 shows a Texas Instruments Silent 700 printing terminal connected to a PCU. This arrangement was used for monitoring the Sytek serial port during the first test phase. In the second phase, the terminal was replaced by a monitoring circuit that detected level transitions on both serial ports by checking all RS-232 lines originating within the modem. The circuit offers the advantage of checking both serial ports simultaneously, as opposed to having a terminal

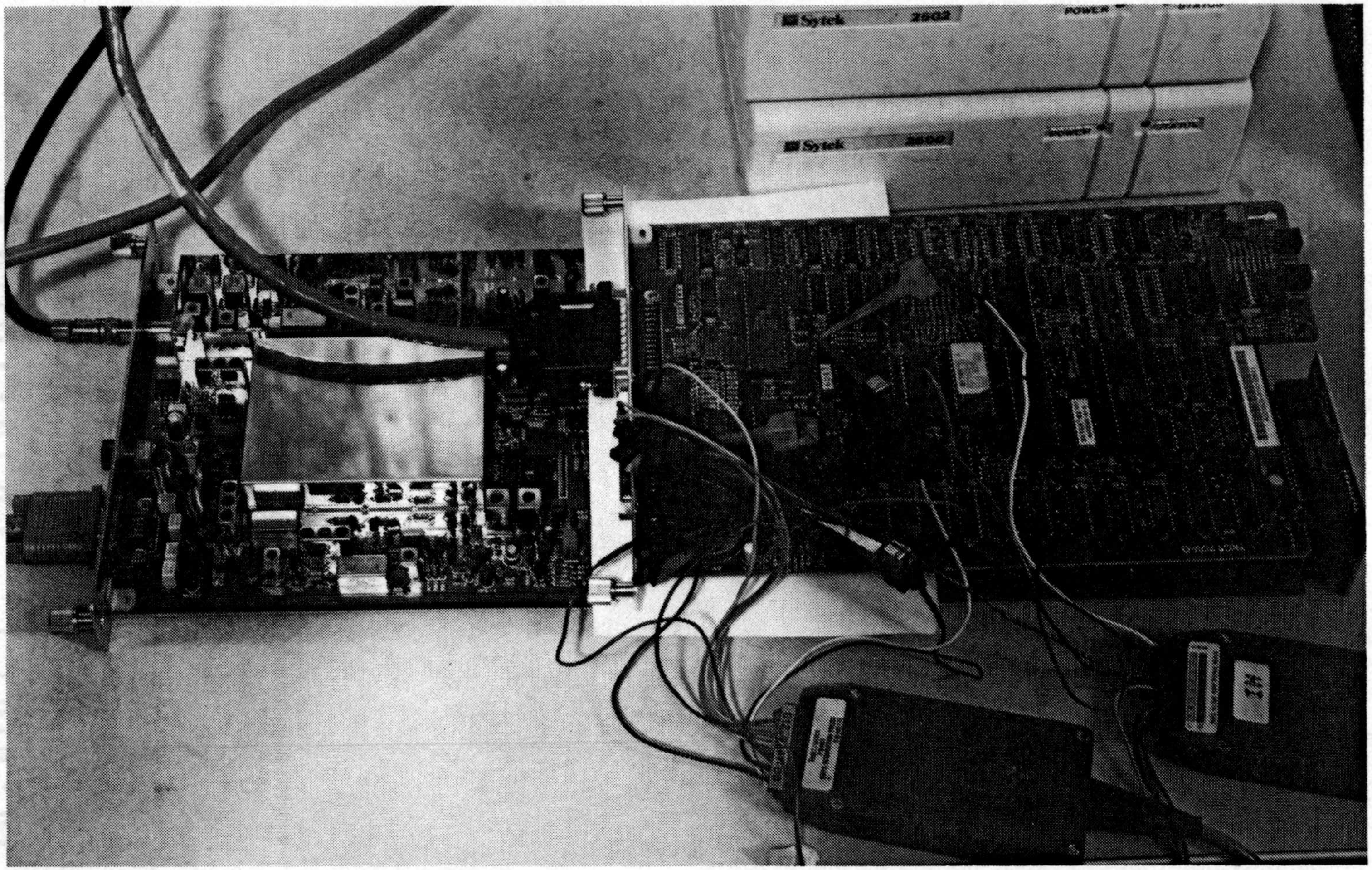

Figure 3.4. The Sytek 2502 PCU modem under test.

plugged into only one port. Furthermore the terminal depends on a full handshaking between devices before a printable character is available. The monitoring circuit checks individual wires and latches an indicator whenever activity is detected. The use of a line monitoring approach provides stronger proof of modem separation because incomplete handshaking events are recorded.

The schematic diagram for the monitor is shown in Figure 3.5. The monitor attaches to those RS-232 lines that originate within the modem. These lines include receive data (RXD) on pin 3, clear to send (CTS) on pin 5, data set ready (DSR) on pin 6, and data carrier detect (DCD) on pin 8. Signal ground is provided by pin 7.

Each signal is routed to the input of an LM1489 line receiver circuit where the $\pm$15-V lines are converted to TTL compatible levels. A converted signal is sent to a 74LS266 exclusive NOR and two 7404 inverter stages for delay. When a signal line is held at a steady level, the inputs to the exclusive NOR are identical and the output is high. During a transition of the level, the change on the lower path reaches the exclusive NOR approximately 20 nsec (2 gate delays) before the signal on the upper path. The delay provides a negative-going pulse that is independent of the original level of the input signal. This pulse sets the $\overline{\mathrm{S}}$ latch of the 74LS279. The output of that latch is buffered by a 7404 to drive a light emitting diode indicator. The latches are manually reset by the push-button on the $\overline{\mathrm{R}}$ input. Monitoring of the second serial port is accomplished by duplicating the circuit.

An additional test instrument not shown in the block diagram is a digital logic analyzer. The logic analyzer was used to monitor data bus activity in the Sytek modem during testing of the digital detection layer.

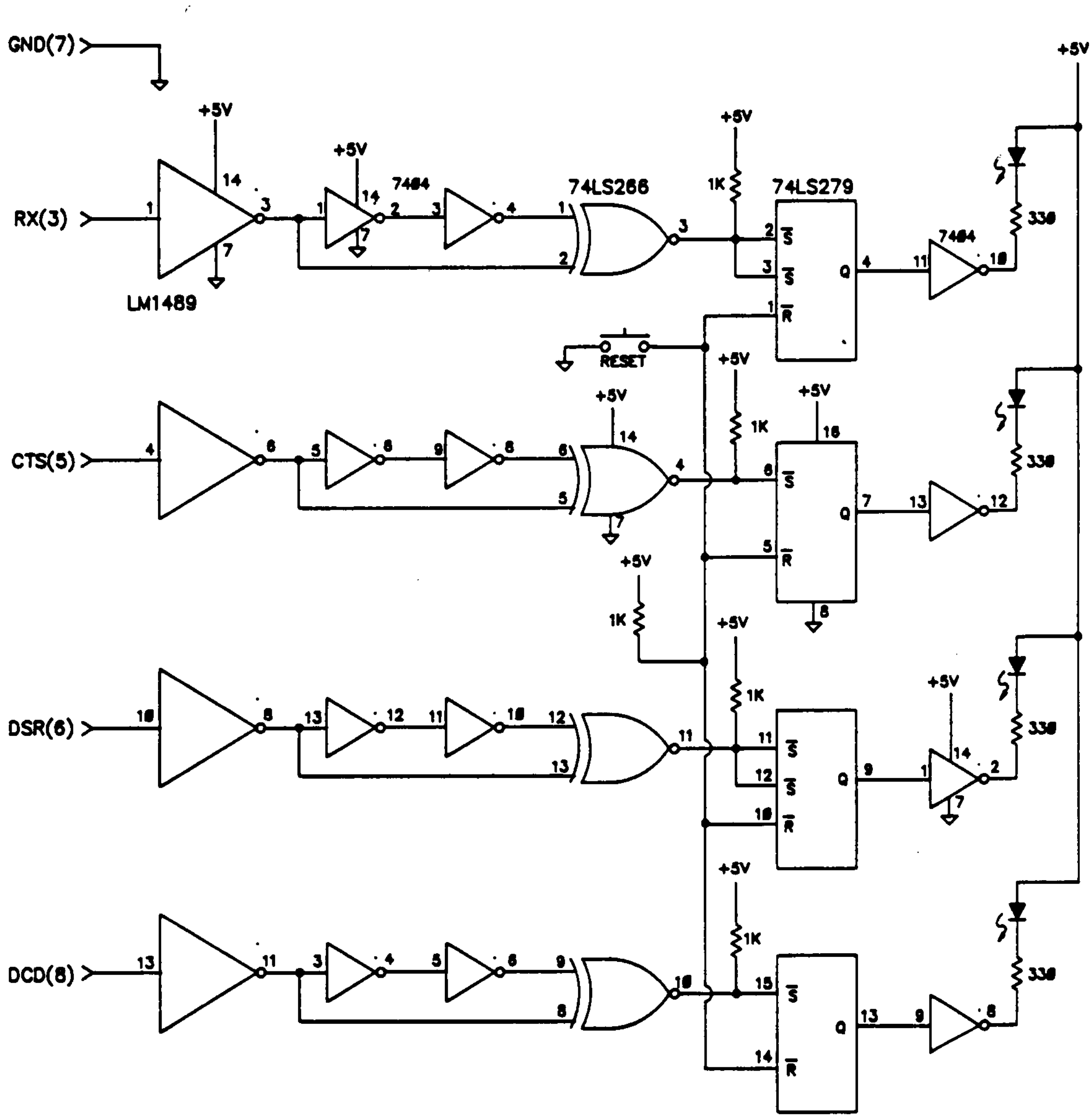

Figure 3.5. Schematic diagram of the RS-232 activity monitor.

A complete listing of equipment used in the test setup and measurements is given in Table 3.1. The equipment is divided into categories of amplifier associated components, passive cable components, network communication equipment, and measurement equipment.

Frequency Separation

It was shown in Chapter 2 that frequency separation isolation is dependent on the characteristics of both the broadband cable system and the modem equipment. The measured spectrum of the operational test system is shown in Figure 3.6. The two peaks correspond to the reverse-channel carriers at 75 MHz and the forward channel carriers at 267 MHz. As a result of operating both modem networks on the same channel, the tip of each channel shows a sharp peak on the left and a broad but lower peak on the right. Figure 3.7 shows an expanded spectrum of the reverse channel. The wide waveform is the power envelope of the Ungermann–Bass modulated carrier. The taller peak above 74 MHz is the Sytek subchannel 12 carrier. As measured at the user tap, the Sytek level is approximately +5 dBmV, and the Ungermann–Bass level is −5 dBmV.

The noise floor of Figure 3.6 is 50 dB below the peak Sytek carrier level. A few spikes are noticeable about 5 dB above the noise floor. The frequencies of these spikes do not correspond to any intermodulation products that are expected from a combination of the two channels and the translator local oscillator. Furthermore, the spikes do not exhibit the symmetry generally associated with intermodulation products. It is likely that the spikes represent bursts of noise near the spectrum analyzer noise floor.

The characteristics of nonlinear intermodulation were well established in Chapter 2. The effects on communication separation were not considered at

Table 3.1 Equipment used in the broadband test network

Component	Type	Vendor	Model/Description
Amplifier components			
Amplifier	Push/pull trunk	Scientific Atlanta	Amp trunk module 231420
Amplifier	Midsplit reverse Trunk with AGC	Scientific Atlanta	Amp trunk module 232660
Amplifier	Push/pull bridging	Scientific Atlanta	Amp trunk module 233170
Amplifier assembly	Trunk	Scientific Atlanta	6560 series
Power supply	Switching regulated	Scientific Atlanta	Amp trunk module 279660
Coaxial cable			
Attenuator	Step	Tektronix	2703/75-Ω
Coupler	Power	Scientific Atlanta	SAIF-RFI
Coupler	Directional	Scientific Atlanta	SADC-12F-RFI
Diplexer	High/low	Blonder–Tongue	MLHF/75-Ω VHF
Power supply	Broadband	Sawyer Industries	1200-6014-1SP-IL/ 60VAC, 14 A
Tap	Distribution	Scientific Atlanta	SAT8-20F-RFI
Communication equipment			
Downloader	PCU	Sytek	2500
NIU	Modem	Ungermann–Bass	180
NIU	Personal	Ungermann–Bass	5331A and 2361A cards
PCU	Modem	Sytek	2502
Translator	Channel	Ungermann–Bass	5517A/Channels 4A and R
Measurement equipment			
Amplifier	CATV	Tektronix	AM511/75-Ω to 50-Ω
Analyzer	Logic	Tektronix	7D01/16 channel
Analyzer	Spectrum	Tektronix	492P/50-Ω input
Counter	Event	Data Precision	5740
Counter	Frequency	Tektronix	DC502
Monitor	RS-232	Crutcher	See Figure 3.5
Oscilloscope	—	Tektronix	7603

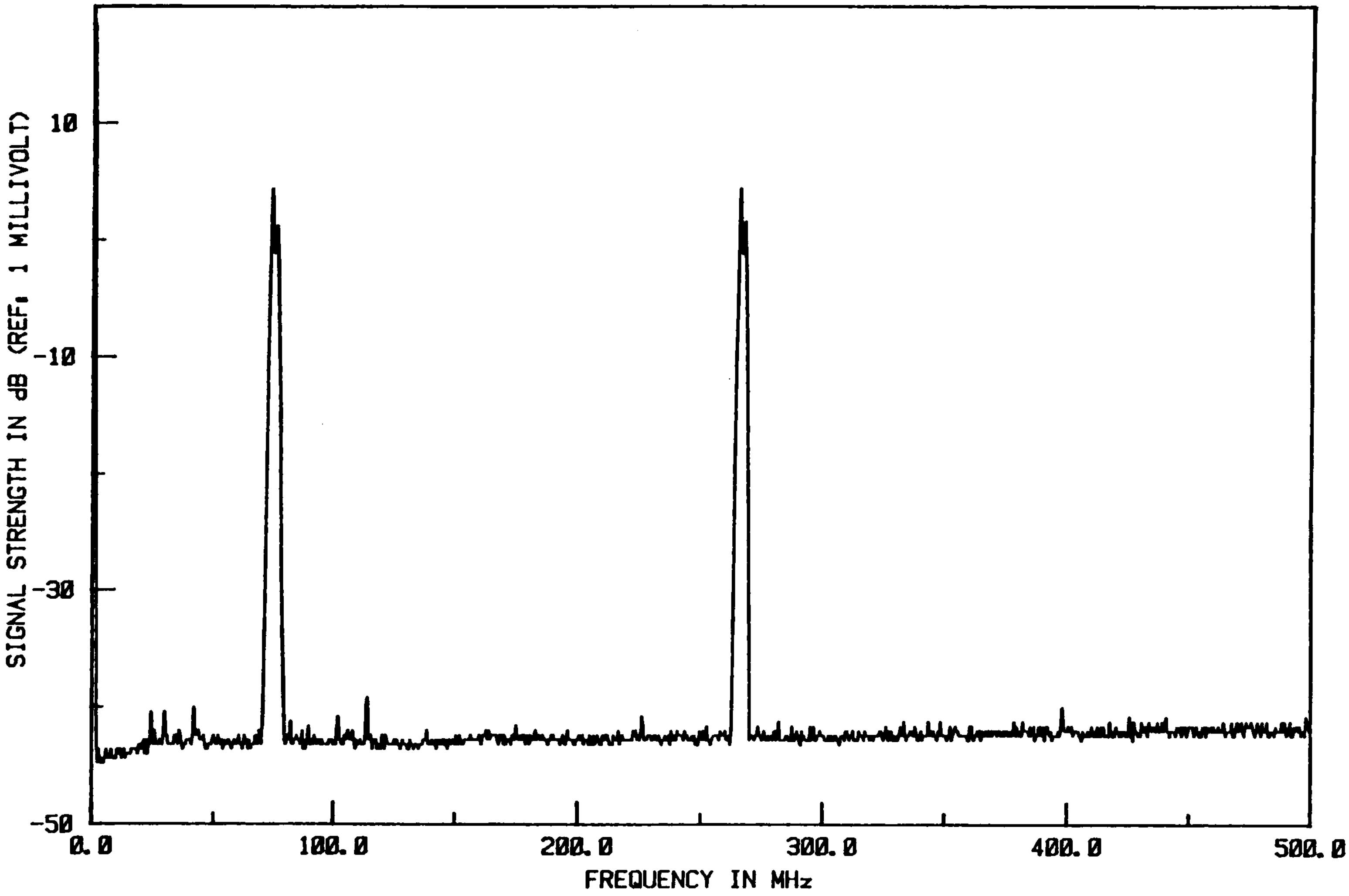

Figure 3.6. Spectrum of the operational broadband test network.

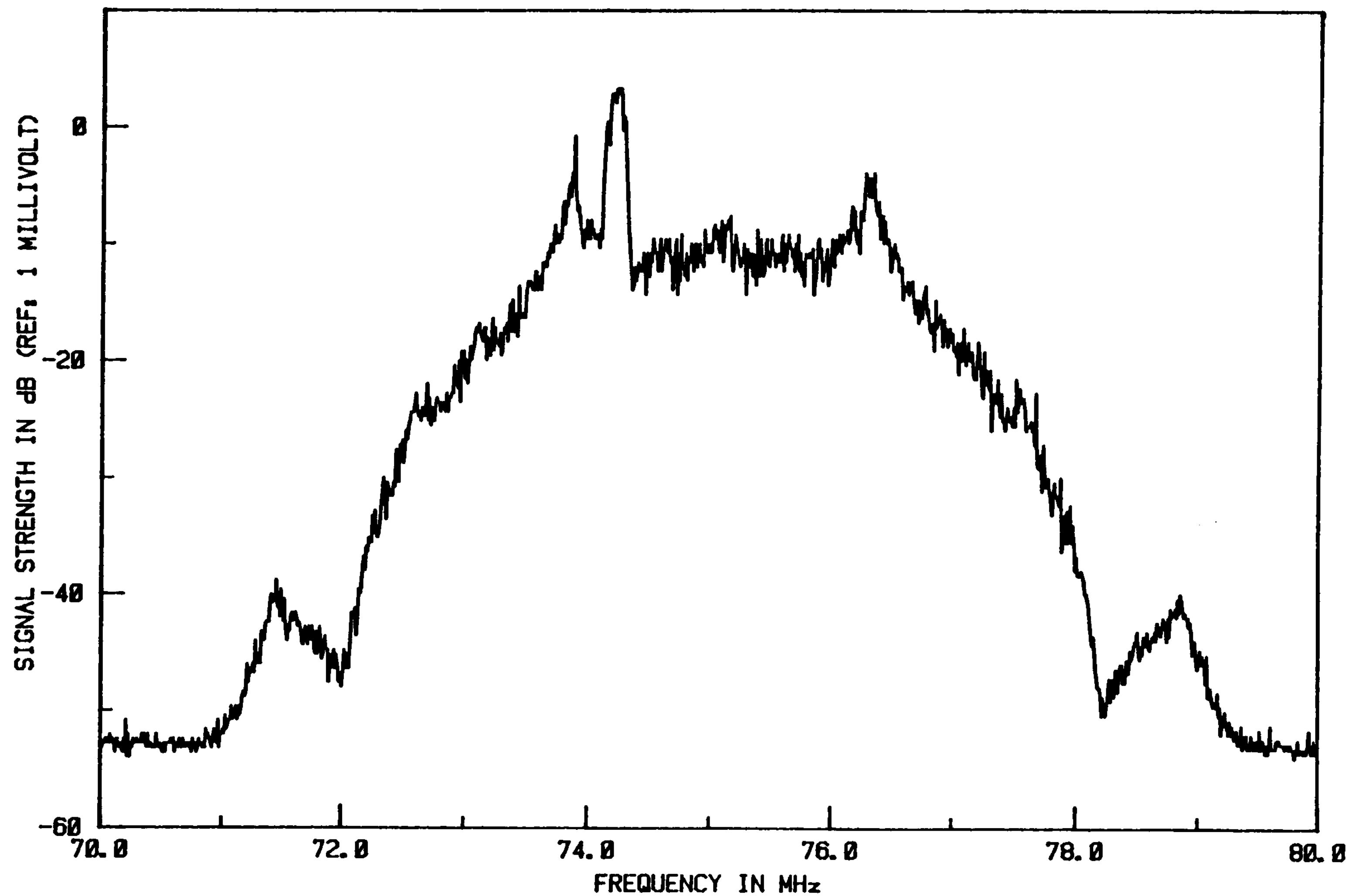

Figure 3.7. Spectrum of the Ungermann–Bass modem with Sytek subchannel 12 superimposed.

that time because equipment performance determines the isolation. For information to bypass the frequency separation layer, three requirements must be met.

The first requirement is that an intermodulation product must be on the frequency of a receiver. Calculations in the previous chapter indicated that while intermodulation products can occur in abundant numbers, the frequencies are predictable by using the intermodulation equation. If intermodulation products do not fall within the passband frequency of a receiver, no information can be transferred. Using the intermodulation equation to locate potential interference is typically done for radio repeater sites where the number of strong local carriers is limited to five or six.[4] The same technique can be applied to a broadband cable system when only a few carriers are present. The example system in Chapter 2, having four television channels and four data channels (12 carriers), demonstrated that avoiding intermodulation terms in a particular frequency bandwidth is difficult, even on moderately loaded systems. The intermodulation equation predicts that multiple interference products occur in every channel on a heavily loaded 36-channel broadband system. On-frequency intermodulation products are more the norm than the exception in all but lightly loaded cable systems.

The second requirement for breakdown of the frequency separation layer is that a mixing product must exceed the minimum sensitivity level of a receiver. An oscilloscope was used to monitor the response of the Sytek receiver's discriminator while the receiver was subjected to interference from an Ungermann–Bass transmitter. Attenuation was added at the Sytek RF input until no response was present. Measurement determined that the interfering signal must be 35 dB below the peak Sytek carrier level to achieve isolation.

Referring to the broadband models of Chapter 2, the −35 dB (referenced to Sytek) level is exceeded for the 10-dB compression of Figure 2.9, the 3-dB clipping of Figure 2.11, and the rectification of Figure 2.13. The guideline for intermodulation products on a broadband system is 59 dB below peak carrier levels.[7] If the receiver will respond to intermodulation products that are 35 dB below peak carrier levels and the standard requires intermodulation products to be 59 dB below these levels, then a 24-dB isolation margin exists under normal operating conditions. This standard, however, is based on peak visual carrier levels. The levels of data carriers must be reduced to prevent the power spectrum within a 6-MHz channel from exceeding that of a normal television signal. Because the Ungermann–Bass modem generates a 6-MHz wide signal with rich spectral content, the carrier is normally reduced by 15 dB from the peak visual carrier level. The recommended formula for reducing the Sytek carrier level is 10 log n in dB, where n is the number of subchannels within a 6-MHz television channel assignment.[14] The reduction can range from 0 dB for a single subchannel to 13 dB if all 20 subchannels are allocated. The broadband model in Chapter 2 used a derating factor of 10 dB for the Sytek carriers, but the signal level of a carrier will affect only the relative amplitudes, not the existence, of intermodulation products.

The threshold level of 35 dB below peak carrier is a function of the receiver noise floor, which is a constant. If the Sytek carrier level is derated because of multiple subchannels, the 35 dB range will be reduced by the same amount. The net margin for a system operating within specifications is still 24 dB because neither the peak visual carrier reference level nor the Sytek receiver sensitivity changed. The ratio between peak Sytek carrier and any intermodulation product is reduced.

The ratio of Sytek carrier level to intermodulation product level requires some explanation. The Sytek modem uses FSK modulation, making it insensitive to amplitude fluctuations. Furthermore FM systems exhibit a property called capture effect, which allows a receiver to lock onto the stronger of two signals while ignoring the weaker. The capture ratio can be as low as a few decibels, providing rejection of strong intermodulation products when a carrier is present. The Sytek network uses CSMA/CD signaling, and no carrier is present when the channel is not in use. A strong intermodulation product on that channel will be treated as a transmitted signal and will be rejected only during those times when actual communications are in progress.

The third requirement for a breakdown in the frequency separation isolation layer is that recoverable modulation must be present on the intermodulation product. Heterodyning, the simplest form of intermodulation, uses a continuous-wave (CW) local oscillator as one of the two inputs. Because the local oscillator is a pure sinusoid, the modulation characteristics of the second input are preserved. If both inputs are FM, a resultant intermodulation product will have a frequency based on the instantaneous frequencies of the two carriers. Two FM signals with the same deviation will produce a second-order component that combines the modulations. Recovered data from the resultant intermodulation product will be the sum (or difference) of the two original signals. Higher-order products exhibit a different characteristic since the deviation of the FM signal is multiplied for harmonics. A fifth-order product composed of $4f_1 - f_2$ terms has four times the deviation from the first signal as from the second. Receiver bandwidth and demodulator characteristics may distort the recovered signal from the wider deviation, but the wider deviation will provide the primary influence.

A typical broadband system can contain AM (television visual), FM (television aural), AM/PSK (Ungermann–Bass Net/One), FSK (Sytek LocalNet), and CW (amplifier pilot carriers) all on the same cable. The resultant modulation characteristics in a nonlinear environment will depend upon which modulation types are mixed and the harmonics that are involved to produce a given order. As a result, some components will provide a recoverable modulation and appear as a signal while others emerge as interference. Performing an analysis for predicting which signals can be recovered serves little purpose because the characteristics of the nonlinearity determine the relative strengths of the harmonic components and will affect the modulation relationships for both amplitude and bandwidth.

Despite the potential for nonlinear intermodulation products, the frequency isolation layer provides an excellent level of protection in a properly operating cable system. Measurements show that the Sytek receiver exhibits a 24-dB margin of rejection for normal system operation. A malfunctioning broadband system can easily produce interference levels 35 dB below peak carrier levels, and while such interference will be evident on video channels, it could go undetected by data channel users. If frequency separation is the only method for providing isolation, the broadband must be monitored continuously for intermodulation products. It is necessary that this monitoring be performed over the entire cable bandwidth and include signal levels that are near the cable noise floor. If a high level of data protection is to be assured, other methods of isolation are recommended. The mixed-modem approach, with the added layers of isolation, is one solution.

RF Bandwidth and Modulation

Analysis performed in Chapter 2 indicated that isolation is obtained from RF bandwidth and modulation differences in the two modem types. Bandwidth measurements will be discussed first, followed by modulation results.

RF Bandwidth Measurements on the Modems

The Ungermann–Bass modem design uses an entire 6-MHz television channel for one data channel. Figure 3.8 shows the spectrum of the Ungermann–Bass reverse data channel as sent from the modem to the translator. The main spectral energy content falls within the 6-MHz bandwidth between 72 and 76 MHz. The peaks at 71.5 and 78.5 are modulation sidebands that fall outside the channel bandwidth. The measured spectrum exceeds the width of the specified spectrum that was established in the bandwidth characteristics section of Chapter 2. The spectrum for the forward Ungermann–Bass channel, from the translator to the modems, is shown in Figure 3.9. The translator filter has removed the two peaks that were outside the channel and has steepened the slope of the main envelope for values approaching the band edge. Except for the filtering, the two spectra are identical.

The Sytek carriers in the reverse direction are shown in Figure 3.10. Twenty carriers on subchannels 6 to 25 are placed in the same 6-MHz bandwidth that was occupied by one Ungermann–Bass carrier. The Sytek modems used in the test are frequency agile and can be tuned to any of the 20 independent subchannels from the modem command level.

Figure 3.11 shows the spectral envelope of a modulated Sytek modem operating on subchannel 6 in the reverse direction. The scale of the spectrum analyzer has been expanded to emphasize the modulation. Spectra for Sytek

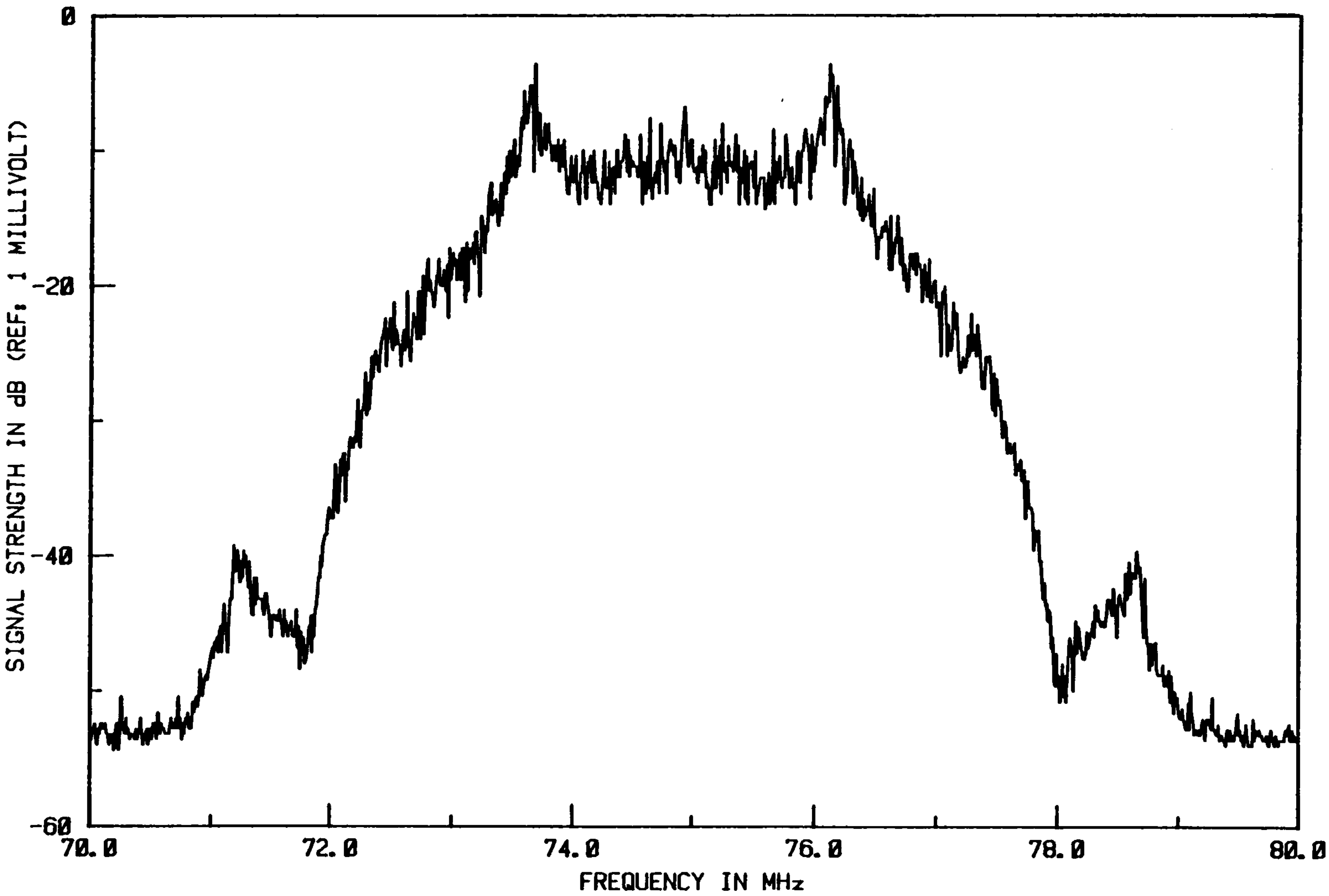

Figure 3.8. Spectrum of the Ungermann–Bass reverse channel.

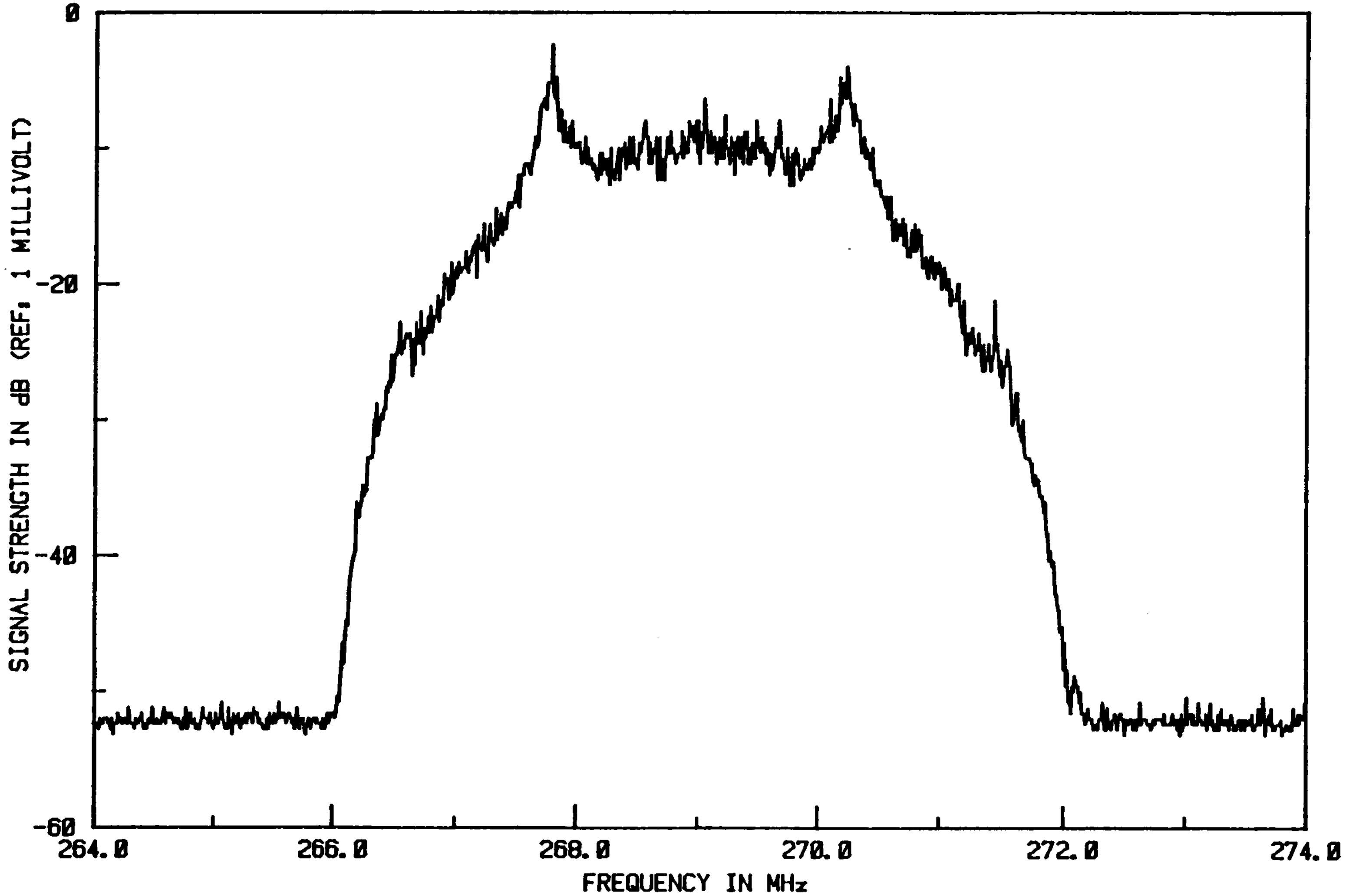

Figure 3.9. Spectrum of the Ungermann–Bass forward channel.

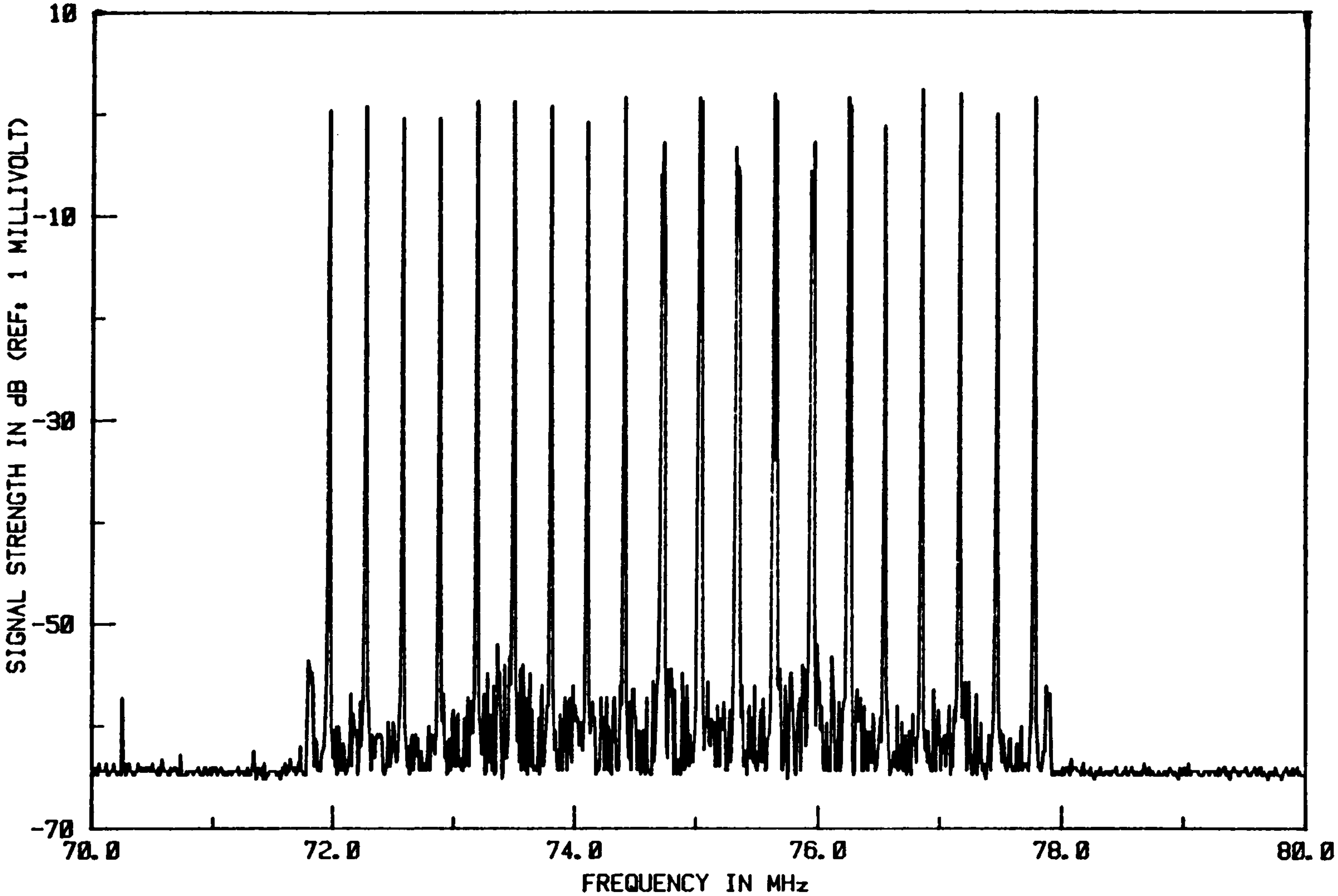

Figure 3.10. Spectrum of 20 Sytek reverse carriers in a 6-MHz bandwidth.

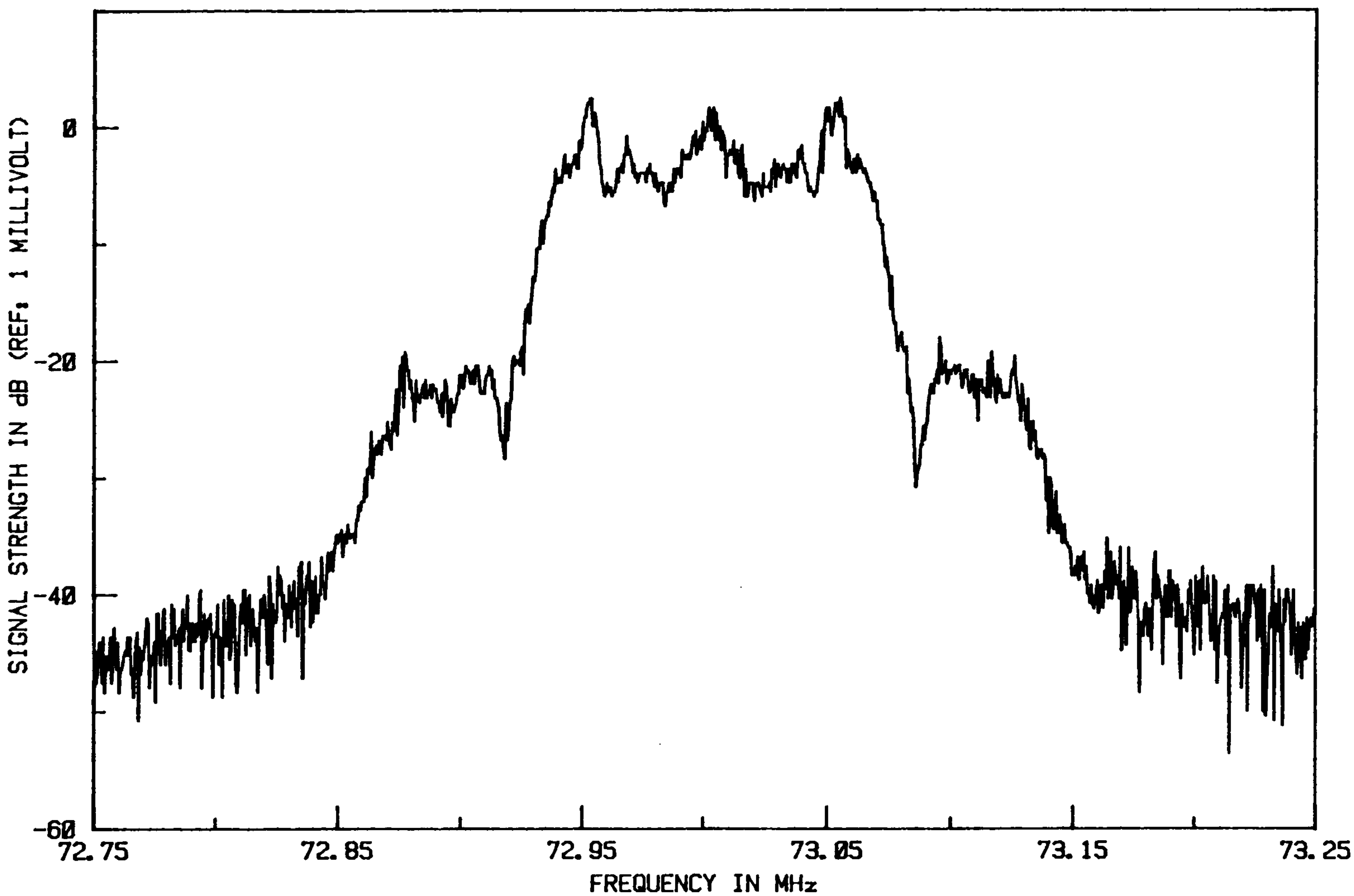

Figure 3.11. Spectrum of Sytek reverse subchannel 6.

reverse subchannels 12 and 25 and Sytek forward subchannel 12 are shown in Figures 3.12-3.14. The same spectral content exists for each frequency, demonstrating that the modulation characteristics are preserved during a frequency shift among the subchannels and through the translator. Verification that the modulation characteristics are maintained with frequency shift is necessary to assure that measurements made on one channel are valid when operating on other channels or in other portions of the broadband cable.

A comparison of the bandwidth ratio for the two modem types can be obtained by referring to Figure 3.7, where the two carriers are superimposed. The modulated Sytek carrier is quite narrow as compared to the total Ungermann–Bass spectral envelope. The Sytek spectral power envelope in Figure 3.11 is 170 kHz wide at the first major nulls and is 300 kHz wide at 35 dB below peak carrier level. The Ungermann–Bass spectral envelope is 6 MHz wide at the first nulls, which coincides to 35 dB below peak carrier level. Comparing Ungermann–Bass and Sytek transmitter outputs indicates a bandwidth ratio of between 20:1 and 35:1, depending upon the point on the envelope where the width is measured.

The bandpass response of the Sytek receiver was measured to provide a better definition of the effective Ungermann–Bass to Sytek bandwidth and to establish an accurate model of the Sytek receiver filter used in the calculations of Chapter 2. An RF signal generator was set to slowly sweep the forward channel frequency around 268 MHz. The spectrum analyzer was capacitively coupled to the output of the Sytek intermediate frequency (IF) stage prior to the demodulator. This test provided a characterization of the modem from the RF input through the RF amplifier, the downconversion mixer, the IF amplifier, and the 10.7 MHz ceramic IF filters.

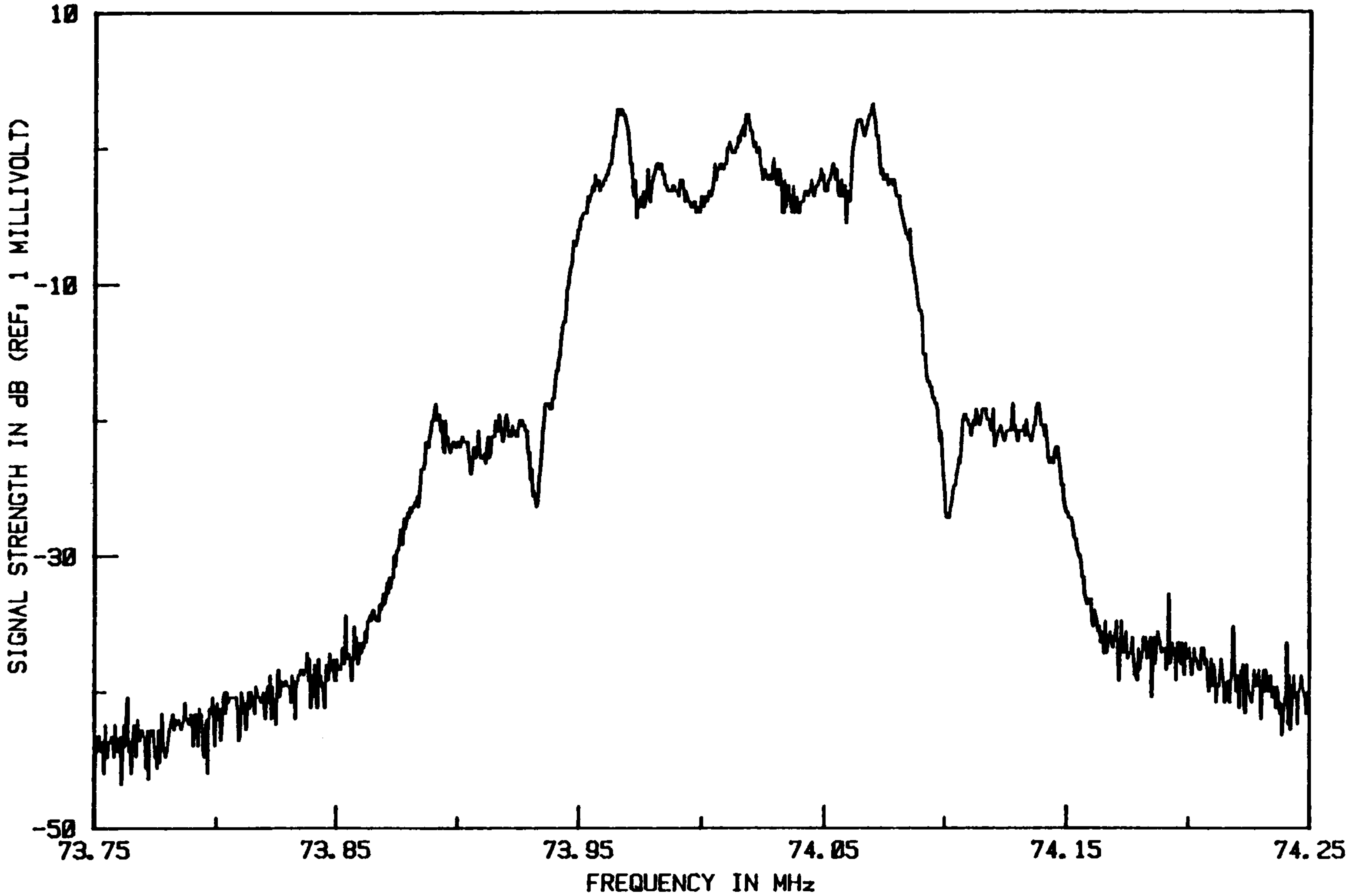

Figure 3.12. Spectrum of Sytek reverse subchannel 12.

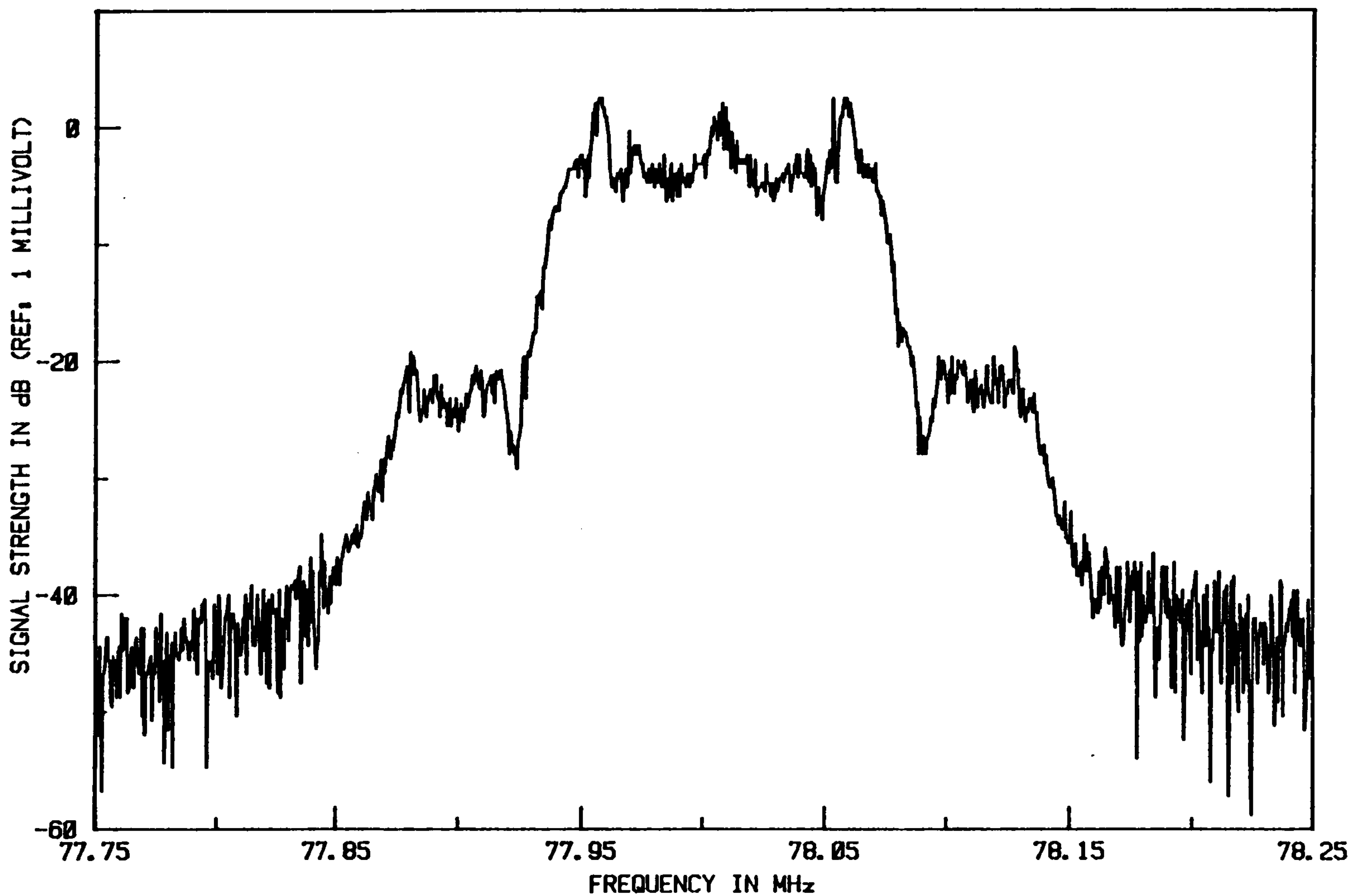

Figure 3.13. Spectrum of Sytek reverse subchannel 25.

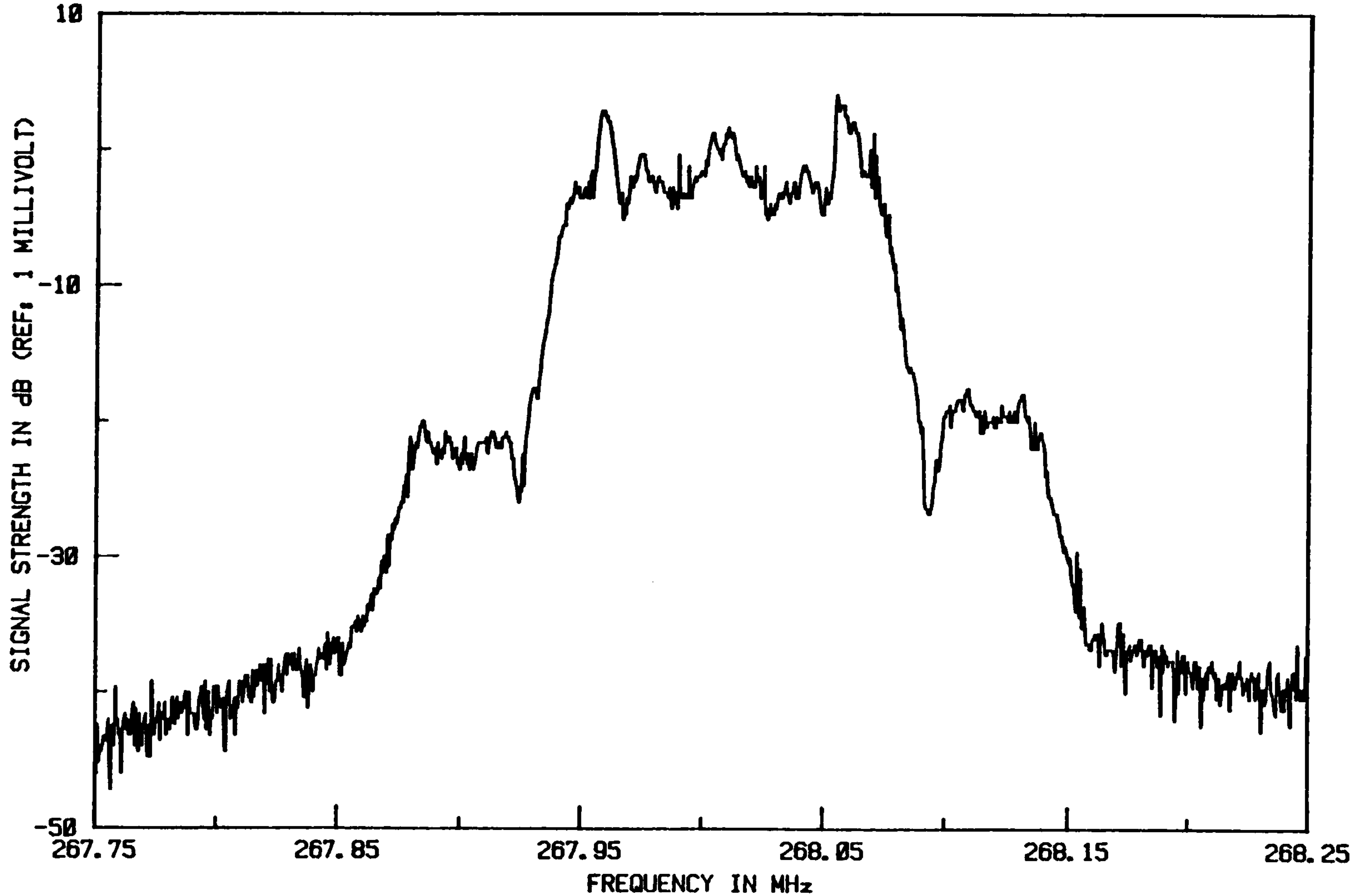

Figure 3.14. Spectrum of Sytek forward subchannel 12.

Figure 3.15 is a plot of the bandpass characteristic of the RF and IF stages of the Sytek modem. The 3-dB bandwidth is approximately 180 kHz, roughly equal to the first-null bandwidth of the transmitter. The 300-kHz bandwidth is approximately 22 dB below the peak level, and the 50-dB points fall at a 450-kHz bandwidth.

Comparison of the transmitter and receiver measurements showed the effective ratio of Ungermann–Bass to Sytek bandwidth to be roughly 20:1. Predictions were made in Chapter 2 that the effect of the filtering would distort the signal beyond recovery. Oscilloscope measurements at the output of the Sytek discriminator showed that the receiver provided a response to the Ungermann–Bass signal. The pulse widths ranged from 1.8 μsec to 16.4 μsec, with the median time around 8 μsec and the average time at 7.5 μsec. The pulse response from a Sytek data transmission ranged from 14.0 μsec to 20.4 μsec, with a median and average around 17 μsec. The typical pulse widths of the Ungermann–Bass response are approximately one-half those of the Sytek data response although the Ungermann–Bass data symbol rate at the broadband interface is 20 times that of the Sytek modem.

The 1:2 pulse width ratio varies by a factor of 10 from the transmitted signal. This difference is explained with an extension of the filtering model developed in Chapter 2. The filter characteristics of the Sytek receiver are sharp and narrow as compared to the Ungermann–Bass spectrum. If the Sytek filter is approximated as a narrow rectangular window in the frequency domain, the time-domain representation of the signal will be the data stream convolved with a $\frac{\sin x}{x}$ function. Because the pulse width and frequency are related as reciprocals, the effective pulse response of the filter is on the order of that required by Sytek data. Convolution of the filter function with the high-speed data accounts for a greater

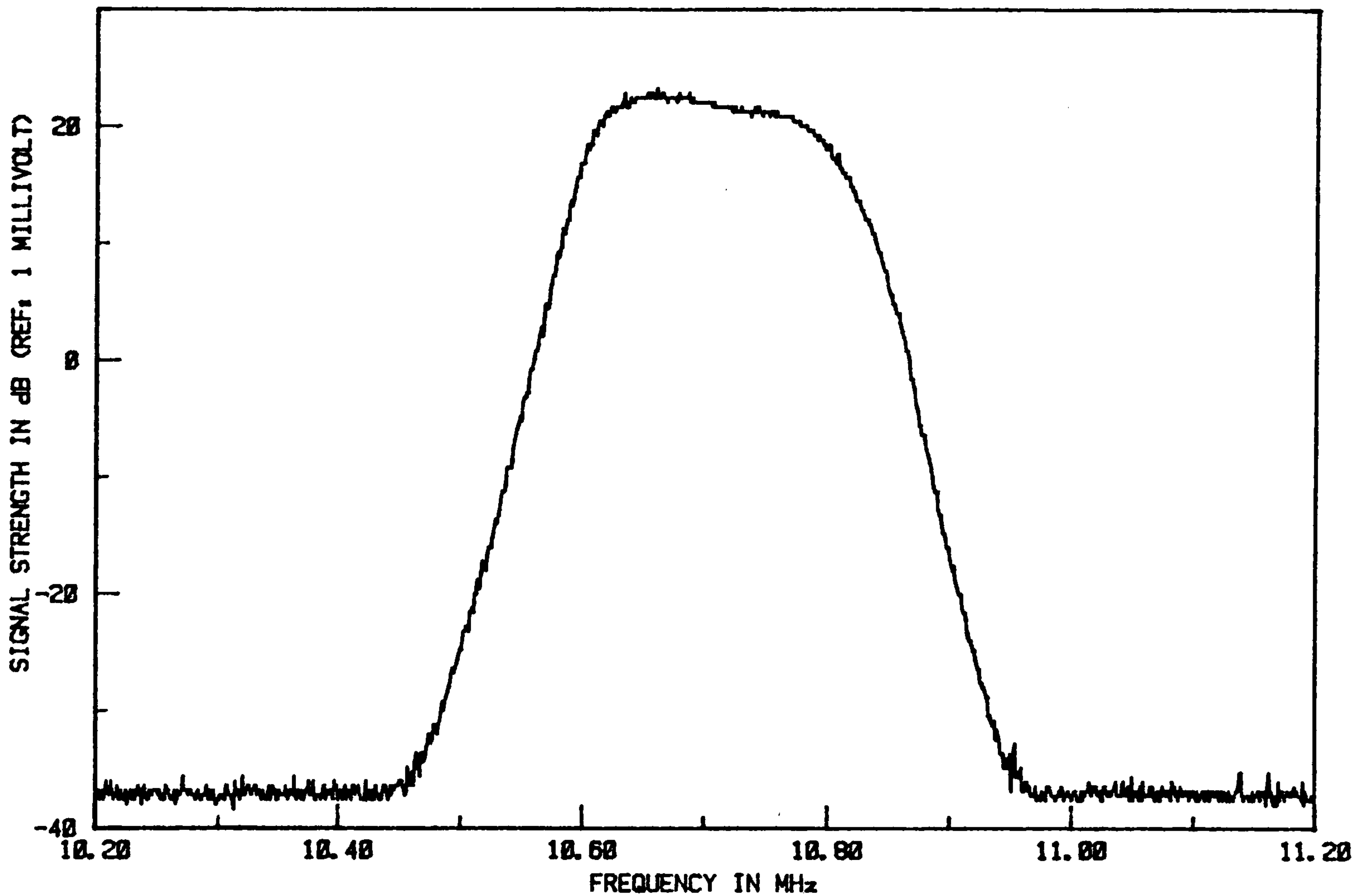

Figure 3.15. Bandpass characteristic of the RF/IF stages of the Sytek modem.

variation in the individual pulse widths. Measured performance indicated that the Sytek receiver filters severely distort the Ungermann–Bass data and provide a response strongly dependent upon the filter characteristic with slight variations produced by the data.

RF Modulation Measurements of the Two Modems

The Ungermann–Bass modem uses duobinary AM/PSK modulation, and the Sytek modem uses a phase-continuous FSK, but both are implemented under a CSMA/CD protocol. An interesting similarity exists between the spectral power envelopes of Figure 3.8 and Figure 3.11 when an adjustment is made for bandwidth. Although these plots represent only the peak magnitude of the spectrum and were collected over several minutes, the time-weighted peak spectrum provides the response of the transmit filters to changing data. Both spectra have sidebands characteristic of digital data, and both are limited by bandwidth filtering. With these considerations the peak spectral envelopes should be similar.

The instantaneous magnitudes of the carriers are difficult to measure because of the swept-filter design of an RF spectrum analyzer. A single sweep provides a spectrum in which the amplitude is sampled as the filter sweeps across the frequency. The data, and therefore the instantaneous spectrum, are changing during the sweep, providing a compound representation with small segments of many instantaneous spectra. This error, when coupled with the lack of phase information, makes comparative measurements of the instantaneous spectra impractical.

The analysis of Chapter 2 predicted that the PSK modulation would be treated as impulse FSK, but the limited bandwidth of the receiver filter slows the phase changes and prevents true impulses from being detected. The transformed filter characteristic exhibits a strong influence on the demodulated signal with the result being digital pulses with wide timing variations.

The discriminator output was monitored while the receiver was operated on several Sytek subchannels. Both the occurrence of pulses and the width of the pulses changed with frequency. The spectral activity within the Ungermann–Bass channel directly affects the recovered digital sequences. This observation corresponds to the theoretical results presented in Figure 2.16 in which the position of the filter within the spectrum determines the characteristics of the waveform. Figure 2.16(b) predicts a broad waveform when operating on the edge of the band. During measurements, the Sytek modem did not respond to Ungermann–Bass signals when operated on the band-edge subchannels 6 and 25. The other three waveforms in Figure 2.16 indicate areas with flattened response, a characteristic that could account for the variability of the pulse widths.

An additional aspect of the digital encoding must be considered. The original Ungermann–Bass signal was duobinary encoded with a three-level code. Accurate recovery of the original data requires two thresholds for obtaining the three levels, plus application of the decoding algorithm to reconstruct the original bit sequence. The Sytek demodulator provides only one threshold and two levels, producing a binary output. A recovered bit sequence will not agree with the original, even in the absence of other distortions.

Before finishing the discussion of modulation, an interesting phenomenon that was observed during testing will be discussed. Oscilloscope measurements were originally made on several signals between the RF receiver and the digital processing board. When Ungermann–Bass data were used in place of Sytek data, a major difference occurred on the Sytek receiver's carrier detect line. The carrier detect signal controls channel access under the CSMA/CD scheme and is typically a 5.5-msec wide pulse for a Sytek transmission but drops to 200 μsec width during an Ungermann–Bass transmission. This ratio of 27.5:1 is sufficiently short to abort data recovery activities in the Sytek modem. These shortened carrier pulses, combined with shortened and variable data widths, create a phase jitter on the Sytek receive-data clock. This jitter was sufficient to keep the receiver from locking onto the pulses.

The combined differences in filter bandwidth characteristics, RF modulation methods, and digital encoding/decoding schemes form a strong second layer of isolation protection. Altered signal and control timing of the recovered waveform will be shown to affect later isolation layers.

Digital Data Detection Measurements

The third layer of isolation is provided by the serial-to-parallel conversion of the SIO chip. As described in the bandwidth and modulation section, a digital output is available from the Sytek receiver when transmitting Ungermann–Bass data. The digital waveform has pulses that are shorter than the normal Sytek data and are more variable in length. Analysis of the SIO output is required to determine the level of isolation that is achieved by the circuit.

To measure the output of the SIO, a digital logic analyzer was connected to the 8-bit digital data bus of the Sytek modem. The Z80 microprocessor runs at a 6-MHz clock speed, making analysis of total bus activity impractical. Because the output of the SIO represents the data of interest, only those bytes that are sent from the SIO need be analyzed. The data output condition exists when the INPUT/OUTPUT REQUEST, CHIP ENABLE, READ, and B/A SELECT pins of the chip are all low.

The circuit of Figure 3.16 was constructed to provide a means of triggering on this output condition. The $\overline{\text{IORQ}}$, $\overline{\text{CE}}$, $\overline{\text{RD}}$, and B/$\overline{\text{A}}$ lines are connected to the input of a CD4002 NOR gate where they are logically ANDed due to the active-LOW states. The output of the NOR gate provides a coincidence detection of the conditions required for SIO output onto the data bus. The detection output is buffered to drive an event counter that tallies the number of bus characters sent from the SIO to the microprocessor.

During a transfer cycle, generally six (but occasionally eight) bytes are placed onto the bus by the SIO. The spacing of these bytes causes the total collected data to exceed the memory of the logic analyzer when attempting to view all six bytes of the event. The CD4017 counter in Figure 3.16 provides a delayed trigger source to begin data capture on a later byte. Triggering from an appropriate output can delay data capture by up to ten SIO bytes in the transfer cycle.

Activity between the Sytek SIO and the microprocessor was monitored for 1595 hours while a total of 2.42×10^{10} bytes were transmitted on the Ungermann–Bass network in the second phase of testing. A file transfer program sent data files that are representative of those typically encountered in an office environment. These files included English text in ASCII form, drawings from Autocad, database entries from dBase III, and spreadsheet data from Lotus 123. Additional testing was performed with program-generated characters timed to simulate keyboard entry from a terminal. Table 3.2, a listing of the data recorded during testing, presents thirty-three individual test sessions that were executed with durations ranging from less than 2 hours to nearly 300 hours.

In Table 3.2, the first column indicates the assigned session identification number, and the second column is the duration of the test in hours. Column three provides the number of megabytes of user data, not including communications

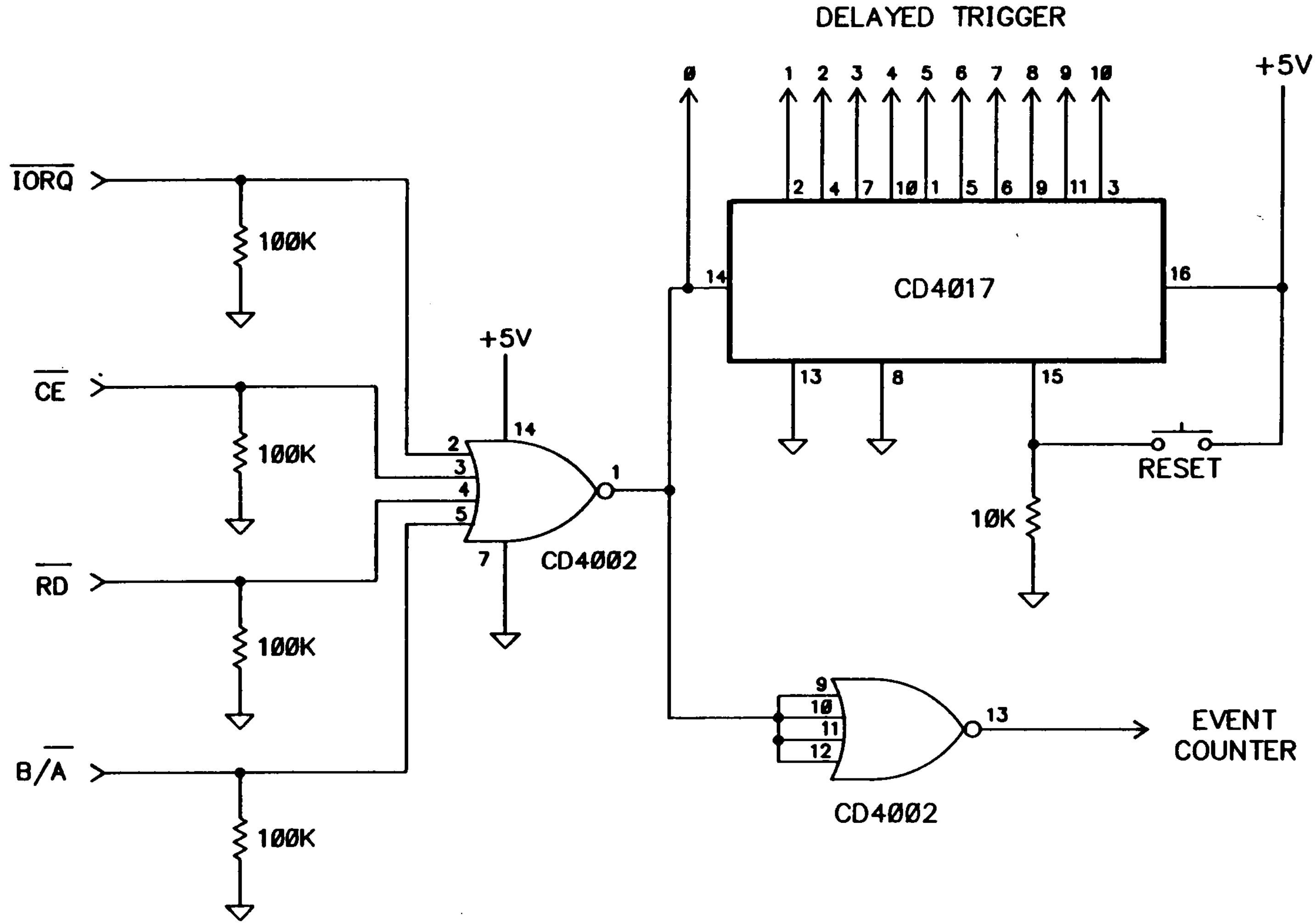

Figure 3.16. Schematic diagram of the bus interface monitor and delay circuit.

Table 3.2 Data from network file-transfer tests

Session no.[a,b]	Duration (hours)	Bytes Transferred ($\times 10^6$)	Ungermann–Bass packets ($\times 10^6$)	Sytek SIO bytes ($\times 10^3$)	Bytes/ count ($\times 10^3$)	Packets/ count ($\times 10^3$)	File type
1	115.32	164.40	14.13	13.33	12.33	1.06	Terminal
2	1.57	30.30	1.93	2.38	12.73	0.81	Terminal
3	14.93	288.60	18.56	23.67	12.19	0.78	Terminal
4	166.77	172.50	16.35	14.44	11.95	1.13	Terminal
5	4.47	86.40	4.55	6.76	12.78	0.67	Terminal
6	17.85	327.60	21.14	25.36	12.92	0.83	Terminal
7	92.57	526.80	36.92	36.65	14.37	1.01	Terminal
8	8.43	162.60	10.48	14.09	11.54	0.74	Terminal
9	14.00	269.70	17.37	23.55	11.45	0.74	Terminal
10	8.37	160.92	10.35	18.83	8.55	0.55	Terminal
11	14.27	70.56	4.90	4.69	15.04	1.04	Terminal
12	3.70	71.40	4.60	4.52	15.80	1.02	Terminal
13	5.40	104.40	6.71	7.72	13.52	0.87	Terminal
14	18.48	121.02	8.19	9.12	13.27	0.90	Terminal
15	6.07	116.16	7.48	8.02	14.48	0.93	Terminal
16	25.07	483.84	31.13	36.03	13.43	0.86	Terminal
17	21.40	48.42	2.74	3.50	13.83	0.78	Terminal
18	22.08	436.38	31.19	18.52	23.56	1.68	Text
19	16.18	334.32	20.48	8.69	38.47	2.36	dBase III
20	26.68	551.64	33.81	14.68	37.58	2.30	dBase III
21	42.65	749.04	54.63	20.39	36.74	2.68	Lotus 123
22	46.13	936.60	58.66	23.36	40.09	2.51	Autocad
23	47.78	922.32	59.35	24.23	38.07	2.45	Terminal
24	3.43	63.96	4.29	0.00	–[c]	–	Autocad
25	4.85	93.60	6.06	0.00	–	–	dBase III
26	6.98	134.76	8.67	0.00	–	–	Terminal
27	89.38	1845.60	113.07	0.00	–	–	dBase III
28	70.72	1462.74	89.52	14.21[d]	102.94	6.30	dBase III
29	94.90	1668.96	121.67	42.20	39.55	2.88	Lotus 123
30	80.40	1631.58	102.81	35.57	45.87	2.89	Autocad
31	164.93	3272.70	210.07	55.70	58.76	3.77	Text
32	45.68	802.80	58.56	14.39	55.79	4.07	Lotus 123
33	293.50	6059.82	371.47	113.75	53.27	3.27	dBase III

[a]Session numbers 1-17 have a variable average character rate to simulate a terminal. The characters-per-hour rate will vary.

[b]Session numbers 24-27 were taken on Sytek subchannel 6. All other sessions were on subchannel 12.

[c]Values are indeterminate because no SIO data bytes were transferred on subchannel 6.

[d]Session number 28 has a low SIO byte count because of triggering adjustment on the counter. All data not dependent on SIO count are accurate.

overhead, transferred by the network during the test. The fourth column gives the millions of Ungermann–Bass transmission packets as monitored on the network controller. The number of these packets is proportional to the quantity of data sent, with two exceptions. First, occasional packets are required to maintain network node connections when user data are not being sent. Secondly, while a packet may contain from 46 to 1500 data characters, the packet efficiency goes down for slower data rates, giving a lower data-character-per-packet ratio.

The fifth column of Table 3.2 lists the number of bytes transferred from the SIO to the microprocessor, measured with the circuit described above. The bytes/count and packets/count columns express the ratios in kilobytes of data and kilopackets of traffic per SIO transfer byte. This ratio provides an indication of the Sytek performance for various types of data files and methods of transfer.

Data in sessions 1–17, 23, and 26 were transmitted with a program to simulate operation of a terminal. The data rate was varied from a few characters per minute to bursts of 60 characters, with random times between the characters. The nature of this program adds variability to the character rate, the characters per SIO byte, and the number of packets per SIO byte. Entries in lines 1–17 generally exhibit 12–15 kilobytes of data for each SIO transfer character. There are between 600 and 1000 packets of traffic for each SIO byte.

Sessions 18–22 and 29–33 used a file transfer program to send data from four types of office-oriented files. The data bytes per SIO character and the Ungermann–Bass packets per SIO character are higher for this mode of transmission. The packets per SIO byte range from 1680 to 4070, with an average of 2841. This compares with a low of 848, a high of 4052, and an average of 2851 for the first phase of testing.[9]

Line 28 contains a low SIO byte count because of an error in adjustment of the counter trigger. The time, bytes transferred, and network packets are correct, but other data for that entry should be disregarded.

Session numbers 24–27 used Sytek subchannel 6, on the lower edge of the Ungermann–Bass band. In 104 hours of testing, no Sytek SIO response was detected—a result consistent with the edge-of-band predictions of the Sytek IF filter model in Chapter 2.

The average number of bytes transferred per SIO response is 14,348 for the terminal mode and 42,968 for the file transfer mode; the number of bytes per packet is roughly equivalent, with 14.9 for the terminal mode and 15.5 for the file transfer mode. Analyzing the data reveals a ratio of transfer mode bytes to terminal mode bytes of 7.2:1, but the ratio of transfer mode SIO events to terminal mode SIO events is only 2.3:1. These ratios imply that slower data rates with varied timing relationships are more likely to cause a transfer of SIO characters to the data bus than data sent at a constant rate. Attempts were made to determine whether the SIO activity was triggered by the data or by some attribute of the packet structure. Conclusive evidence was not obtained to link the phenomenon to either the packet or the data. A determination was made that the Ungermann–Bass transmissions would trigger SIO events for the "empty" packets used to maintain the port connections.

Because the data output from the SIO represents the only means by which the isolation layer can be penetrated, a method for analyzing the six SIO bytes of a transfer cycle is desirable. An attempt to store the six bytes in a FIFO buffer failed because the 6-MHz clock of the microprocessor produced data bus speeds exceeding the capability of the CMOS FIFO chips that were available. The use of a wire-wrapped breadboard added to the speed problem.

In the first phase of testing, the data bus character was reported as being a constant hexadecimal **FF**. This observation was erroneous because the character was read from the bus when the chip setup conditions triggered the logic analyzer's word recognizer. The data bus was inactive at that instant, and the next byte on the bus represented the data. This error was corrected for the second phase of testing. A sampling of 420 events yielded the hexadecimal sequence **00 00 D4 D4 00 00** for 89% of the events, with the remaining 11% showing no emerging patterns in the data. An interpretation of this byte pattern was not found in the SIO programming manual.

The transient rejection circuitry acts on the shortened and variable pulses at the serial input of the SIO and causes suppression of most of the logic transitions. If the occasional bus events are transfer of what appears to the SIO as acceptable data, the output is determined by a set of independent conditions not directly related to the transmitted data pattern. Such a random input would produce a random output. The consistency of the sequence suggests that the output is a preset code, such as an error message transfer from the SIO to the microprocessor. In either event, the repetitiveness of this code precludes useful information from being propagated further in the modem.

Packet Protocol Measurements

The fourth layer of isolation in the mixed-modem technique is provided by the transmission protocols of the data packets. Comparison and analysis were presented in the protocol discussions of the second chapter.

It was established in the data detection section of this chapter that only one character was sent from the SIO to the microprocessor for every 14,348 characters in the terminal mode or 42,968 characters in the transfer mode. When the transfer of SIO data did occur, the same sequence was present during 89% of the transfers.

The second and third layers of isolation provide sufficient data protection to prevent direct testing of the protocol layer. The frequency separation layer was easily bypassed for testing additional layers, but hardware differences between the two modems preclude a convenient method of bypassing the second and third layers to test protocol isolation. Further attempts to measure protocol isolation were not made due to the extensive effort that would be involved. Development of an accurate computer model for protocol isolation simulation, coupled with the design of a hardware interface to link the modems on the protocol level, would in itself constitute a thesis topic. For this reason, no specific protocol tests were performed.

Evaluation of Performance

The measurements and data transmission tests described in this chapter support the theoretical predictions made in Chapter 2. Each layer of proposed isolation was shown to exist, and compound conditions within some layers could qualify as two layers.

The desired result is isolation of data, and this performance is best measured by end-to-end system testing. In the second phase of testing, 2.42×10^{10} bytes of user data were sent over the Ungermann-Bass network during a period of 1595 hours. There were 1.56×10^{9} Ungermann-Bass communications packets required for this data transfer. A monitor on the Sytek modem SIO output indicated that Ungermann-Bass data affect the Sytek modem when sufficient RF signal levels are present (first layer bypassed). No data were transferred through the Sytek modem, however, because the RS-232 serial ports did not originate any activity as a result of Ungermann-Bass data. This represents a significant degree of isolation and substantiates the effectiveness of the mixed-modem isolation technique.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Summary

The results of both theoretical analysis and extensive testing show that significant data isolation can be achieved by using different vendor products to obtain multilayered isolation. The technique provides effective isolation and allows users to share a broadband network without the danger of sharing data. The mixed-modem approach uses network interface units (modems) that are unmodified, off-the-shelf hardware, and allows system implementation with nominal expense compared to the expense of two separate broadband systems. The use of multilayer isolation on a shared system eliminates the need for specialized broadband cable monitoring and requires a minimum of administrative control.

Analysis and testing of isolation were primarily performed for data propagation in the Ungermann–Bass-to-Sytek direction. Many of the theoretical details developed in Chapter 2 are valid for the Sytek-to-Ungermann–Bass direction, but direct reciprocity cannot be applied in all cases. Some theoretical models require modification before they can be applied to the reverse direction. Isolation for the Sytek-to-Ungermann–Bass direction exists for the layers described, but the reasons may be different from those given in the detailed analysis. End-to-end data transmission testing in the Sytek-to-Ungermann–Bass direction verified that isolation existed, but the duration of the test was not extensive.

The investigations of Chapter 2 predict that a high level of data protection is available by implementation of a mixed-modem system. Four layers of isolation are achieved by: (1) frequency separation through the use of different RF channels, (2) a 20:1 difference in RF bandwidth and incompatibilities in modulation and data encoding schemes, (3) the effects of shortened pulses and variable pulse timing on digital data conversion to a parallel format, and (4) incompatibilities in the protocols used for packet transmission.

The frequency separation layer is equally valid for transmission isolation in either direction. If the linearity of the RF system is sufficient to suppress intermodulation products, then no cross-modulated RF signals are present on either channel of operation. A computer model demonstrated that the frequency separation layer can be bypassed in the event of a system hardware failure. The symmetry of the mathematical relations associated with intermodulation predicts that if this layer breaks down due to nonlinearity, isolation is lost in both directions. The potential vulnerability of the frequency separation layer provides justification for the additional protection provided by the mixed-modem technique.

RF bandwidth and modulation were shown to provide two layers of isolation although they are listed as one to preserve compatibility with previous publications. The relatively narrow (by Ungermann–Bass standards) receiver filter in the Sytek modem produces intersymbol interference in the Ungermann–Bass signal by spreading the pulse widths of the received data. Analysis with the aid of a computer model demonstrates that the output waveforms are more dependent on the receiver filter than on the data. These filter distortions do not exist in the Sytek-to-Ungermann–Bass direction, but the narrow Sytek carrier will appear as a fixed carrier in a portion of the Ungermann-Bass band. Modulation isolation for the Ungermann–Bass-to-Sytek direction was based on duobinary encoding and an AM/PSK signal applied to an FSK receiver. Data are lost by the lack of duobinary decoding, and the AM/PSK has the effect of producing an impulse FSK modulation. In the reverse direction, the Ungermann–Bass modem will attempt to make a duobinary signal from a waveform that was not encoded, and the center level of the duobinary code will be incorrect. The FSK signal will produce a triangular PSK phase relationship. Two additional factors enter into transmission in this direction, however. First, the frequency deviation of the Sytek FSK signal is insufficient to produce a phase modulation with characteristics near those of a normal Ungermann–Bass transmission. Secondly, the FSK has a continuous amplitude while transmitting, and no AM component will be detected by the Ungermann–Bass modem. The combined bandwidth, coding, and modulation differences form a strong layer of isolation in both directions.

The digital detection layer discussed in Chapter 2 is centered around the transient rejection of the Sytek receiver's serial-to-parallel interface circuit. Signal incompatibilities and distortions of the data create pulse widths that do not conform to the timing constraints of the interface. The signal entering the circuit exhibits time variations that cause the waveform to be rejected as impulse noise. The Ungermann–Bass modem does not use the same technique as Sytek for digital detection, and no direct comparison has been made on this level for reverse isolation.

The fourth layer of protection analyzed is the packet transmission protocols. Ungermann–Bass uses the IEEE 802.3 format with salient features being a user data packet of 46 to 1500 bytes, 6-byte address codes, and a 32-bit cyclic redundancy code. The Sytek modem uses a protocol unique to Sytek with 0 to 64 user data bytes in a packet, 2-byte address codes, and a 16-bit cyclic redundancy code. Analysis of the protocols indicates that strong isolation is obtained on this level in both directions.

Testing of the separation was performed on an independent broadband network. The frequency isolation layer was bypassed to provide a means for testing the additional layers. Tests performed on the RF bandwidth and modulation layer indicated that a signal was present at the Sytek receiver discriminator output, but the signal did not resemble Ungermann–Bass data.

Measurement of the digital detection layer indicated that no user data were available on the parallel bus of the Sytek microprocessor. A repeating code was occasionally sent from the SIO, but for file transfers this represents only one byte in 46,000 data bytes. The effectiveness of the second and third layers prevented testing of the protocol layer, but analysis predicts that the isolation exists.

The test network was operated for 1595 hours while over 2.42×10^{10} bytes of user data were sent in 1.56×10^{9} Ungermann–Bass communications packets. During this extensive testing, the user serial interfaces of the Sytek were monitored for level changes. The Sytek modem made no attempt to transmit data to the serial ports during these tests. Less extensive testing was performed in the Sytek-to-Ungermann–Bass direction. Again, no serial data were sent from the Ungermann–Bass user ports, but the network monitor did detect frequent cyclic redundancy code errors. These errors indicate that the Sytek carrier was affecting Ungermann–Bass operation, either directly or by interfering with normal Ungermann–Bass communications.

Conclusions

A significant isolation can be achieved between the Ungermann–Bass and the Sytek modems on a broadband local area network. The isolation is considerably greater than that obtained by only using different frequencies with the same brand of modem. A significant cost advantage can be realized by the mixed-modem approach, but the design must stay within the guidelines and assumptions used for analysis and testing. The Ungermann–Bass-to-Sytek isolation has been verified through both extensive analysis and testing. Isolation in the Sytek-to-Ungermann–Bass direction exists and is considered strong, but a detailed analysis of the isolation and extensive testing is recommended before application of the technique if extreme confidence in the data isolation is required in both directions. For those applications where the data have two sensitivity levels, the networks may be installed without further analysis or testing provided that the higher level of sensitivity is applied to the Ungermann–Bass modems.

A consideration when using any type of network is that all user data are available everywhere on the network. For broadband applications involving sensitive data, physical protection must be provided for both the network and the modems.

The mixed-modem technique described here provides a safe method of using a single broadband cable as a medium for networks with data of differing sensitivity levels. However, the application and implementation of computer security methods are beyond the scope of this thesis. It is recommended that those individuals not familiar with computer security consult a professional in the field before applying this or any other technique when sensitive data are involved.

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LIST OF REFERENCES

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APPENDIX

PROGRAM LISTINGS

```
REM   FIG207.BAS
REM   A PROGRAM TO MODEL A BROADBAND CABLE SYSTEM
REM   MULTIPLE CARRIER MODEL WITHOUT INTERMODULATION DISTORTION
REM   THIS PROGRAM WAS USED TO CREATE FIGURE 2.7 IN THE TEXT
REM   (this program runs under the Microsoft QuickBASIC complier)
REM
REM   $DYNAMIC
      DIM FR(16383),FI(16383)
      DEFINT I-N
REM   assign constants
      NAME$="FIG207"
      PI=3.141592654
REM   10=>1024,11=>2048,12=>4096,13=>8192,14=>16384
      LN=14
      LM=2^(LN-10)
      N=2^LN
      NV2=N/2
      NM1=N-1
      HZ=PI/NV2
REM   assign test data
      FOR K=1 TO N
      I=K-1
REM   enter the rf carrier freq & levels
      FR=0
      FR=FR+SIN(I*HZ*175)+.178*SIN(I*HZ*180) :'CH 7
      FR=FR+SIN(I*HZ*289)+.178*SIN(I*HZ*294) :'CH V
      FR=FR+SIN(I*HZ*12)+.178*SIN(I*HZ*17)   :'CH T8
      FR=FR+SIN(I*HZ*36)+.178*SIN(I*HZ*41)   :'CH T12
      FR=FR+.316*SIN(I*HZ*84)+.316*SIN(I*HZ*277) :'SYTEK
      FR=FR+.178*SIN(I*HZ*75)+.178*SIN(I*HZ*268) :'UNGERMANN-BASS
REM   introduce the nonlinear characteristic
      FR(I)=FR
      FI(I)=0
REM   adjust the spectral placement
      FR(I)=FR(I)*(-1)^I
      NEXT K
REM   call the FFT routine
      DIR=1.
      CALL FFTO(DIR)
      FOR I=0 TO N-1
      FR(I)=FR(I)/N
      FI(I)=FI(I)/N
      NEXT I
REM   print the graph for 500 MHz results
      CALL SCALE
      CALL PLOT
30    IF INKEY$="" THEN 30
      SCREEN 0,0,0
      END
```

```
      SUB FFT0(DIR) STATIC
REM   this subroutine is modified to begin with the 0th element of
the
REM   Fourier arrays.  It should not be substituted for SUB FFT
which
REM   begins with the first element of the arrays.
REM   array FR is the real portion of the Fourier array
REM   array FI is the imaginary portion of the Fourier array
REM   DIR is a forward/inverse director (+ is forward, - is inverse)
      SHARED FR(),FI()
      SHARED PI,N,NV2,NM1,LN
      DEFINT I-N
      J=1
      FOR I=1 TO NM1
      IF I=>J THEN 1
      IM1=I-1
      JM1=J-1
      SWAP FR(JM1),FR(IM1)
      SWAP FI(JM1),FI(IM1)
1     K=NV2
2     IF K=>J THEN 3
      J=J-K
      K=K/2
      GOTO 2
3     J=J+K
      NEXT I
      FOR L=1 TO LN
      LE=2^L
      LE1=LE/2
      UR=1.0
      UI=0.0
      WR=COS(PI/LE1)
      WI=-DIR*SIN(PI/LE1)
      FOR J=1 TO LE1
      FOR I=J TO N STEP LE
      IP=I+LE1-1
      IM1=I-1
      TR=FR(IP)*UR-FI(IP)*UI
      TI=FR(IP)*UI+UR*FI(IP)
      FR(IP)=FR(IM1)-TR
      FI(IP)=FI(IM1)-TI
      FR(IM1)=FR(IM1)+TR
      FI(IM1)=FI(IM1)+TI
      NEXT I
      TUR=UR*WR-UI*WI
      TUI=UR*WI+WR*UI
      UR=TUR
      UI=TUI
      NEXT J
      NEXT L
      END SUB
```

```
        SUB PLOT STATIC
REM     plots the spectral data for the graph
        SHARED FR(),FI(),NV2,NAME$
        DEFINT I-N
        FMAX=0
        TL10=LOG(10)
        FOR I=(NV2)+2 TO NV2+500
        FMAG=SQR(FR(I)^2+FI(I)^2)
        IF FMAX<FMAG THEN FMAX=FMAG
        NEXT I
        FMAX=1.581
        LINE (100,195)-(100,195)
        IPY=200
        IC=0
        FOR I=NV2 TO NV2+500
        FMAG=SQR(FR(I)^2+FI(I)^2)
        FMAG=15+(2*(20*LOG(FMAX/FMAG))/TL10)
        IF FMAG<IPY THEN IPY=FMAG
        IF IPY>195 THEN IPY=195
        IPX=IC+100
        LINE -(IPX,IPY)
        IPY=200
        IC=IC+1
        NEXT I
        LOCATE 1,1
        PRINT NAME$
        DEF SEG =&HB800
        BSAVE NAME$+".PLT",0,&H4000
        END SUB
REM
        SUB SCALE STATIC
REM     draws the box and scale for the graph
        SCREEN 2,0,0
        CLS
        LINE (99,15)-(99,195)
        LINE (100,15)-(100,195)
        LINE -(601,195)
        LINE -(601,15)
        LINE (602,195)-(602,15)
        LINE -(100,15)
        FOR I=15 TO 195 STEP 20
        LINE (95,I)-(100,I)
        NEXT I
        FOR I=100 TO 600 STEP 50
        LINE (I,195)-(I,197)
        IF I=100+INT(I/100)*100 THEN LINE (I,195)-(I,199)
        NEXT I
        LOCATE 1,1
        END SUB
```

```
REM   FIG208.BAS
REM   A PROGRAM TO MODEL A BROADBAND CABLE SYSTEM
REM   MULTIPLE CARRIER INTERMODULATION MODEL
REM   CHANNEL 7 ELEVATED 3 DB INTO COMPRESSION
REM   THIS PROGRAM WAS USED TO CREATE FIGURE 2.8 IN THE TEXT
REM   ALL REQUIRED SUBROUTINES ARE LISTED IN PROGRAM "FIG207.BAS"
REM   (this program runs under the Microsoft QuickBASIC complier)
REM
REM   $DYNAMIC
      DIM FR(16383),FI(16383)
      DEFINT I-N
REM   assign constants
      NAME$="FIG208"
      PI=3.141592654
REM   10=>1024,11=>2048,12=>4096,13=>8192,14=>16384
      LN=14
      LM=2^(LN-10)
      N=2^LN
      NV2=N/2
      NM1=N-1
      HZ=PI/NV2
      DD=1.122^(3)
REM   assign test data
      FOR K=1 TO N
      I=K-1
REM   enter the rf carrier freq & levels
      FR=0
      FR=FR+DD*SIN(I*HZ*175)+DD*.178*SIN(I*HZ*180) :'CH 7
      FR=FR+SIN(I*HZ*289)+.178*SIN(I*HZ*294) :'CH V
      FR=FR+SIN(I*HZ*12)+.178*SIN(I*HZ*17)   :'CH T8
      FR=FR+SIN(I*HZ*36)+.178*SIN(I*HZ*41)   :'CH T12
      FR=FR+.316*SIN(I*HZ*84)+.316*SIN(I*HZ*277) :'SYTEK
      FR=FR+.178*SIN(I*HZ*75)+.178*SIN(I*HZ*268) :'UNGERMANN-BASS
REM   introduce the nonlinear characteristic
      DF=.90
      IF FR>3.97 THEN FR=FR^DF
      FR(I)=FR
      FI(I)=0
REM   adjust the spectral placement
      FR(I)=FR(I)*(-1)^I
      NEXT K
REM   call the FFT routine
      DIR=1.
      CALL FFTO(DIR)
      FOR I=0 TO N-1
      FR(I)=FR(I)/N
      FI(I)=FI(I)/N
      NEXT I
```

```
REM     print the graph for 500 MHz results
        CALL SCALE
        CALL PLOT
30      IF INKEY$="" THEN 30
        SCREEN 0,0,0
        END
```

```
REM    FIG209.BAS
REM    A PROGRAM TO MODEL A BROADBAND CABLE SYSTEM
REM    MULTIPLE CARRIER INTERMODULATION MODEL
REM    CHANNEL 7 ELEVATED 10 DB INTO COMPRESSION
REM    THIS PROGRAM WAS USED TO CREATE FIGURE 2.9 IN THE TEXT
REM    ALL REQUIRED SUBROUTINES ARE LISTED IN PROGRAM "FIG207.BAS"
REM    (this program runs under the Microsoft QuickBASIC complier)
REM
REM    $DYNAMIC
       DIM FR(16383),FI(16383)
       DEFINT I-N
REM    assign constants
       NAME$="FIG209"
       PI=3.141592654
REM    10=>1024,11=>2048,12=>4096,13=>8192,14=>16384
       LN=14
       LM=2^(LN-10)
       N=2^LN
       NV2=N/2
       NM1=N-1
       HZ=PI/NV2
       DD=1.122^(10)
REM    assign test data
       FOR K=1 TO N
       I=K-1
REM    enter the rf carrier freq & levels
       FR=0
       FR=FR+DD*SIN(I*HZ*175)+DD*.178*SIN(I*HZ*180) :'CH 7
       FR=FR+SIN(I*HZ*289)+.178*SIN(I*HZ*294) :'CH V
       FR=FR+SIN(I*HZ*12)+.178*SIN(I*HZ*17)   :'CH T8
       FR=FR+SIN(I*HZ*36)+.178*SIN(I*HZ*41)   :'CH T12
       FR=FR+.316*SIN(I*HZ*84)+.316*SIN(I*HZ*277) :'SYTEK
       FR=FR+.178*SIN(I*HZ*75)+.178*SIN(I*HZ*268) :'UNGERMANN-BASS
REM    introduce the nonlinear characteristic
       DF=.90
       IF FR>3.97 THEN FR=FR^DF
       FR(I)=FR
       FI(I)=0
REM    adjust the spectral placement
       FR(I)=FR(I)*(-1)^I
       NEXT K
REM    call the FFT routine
       DIR=1.
       CALL FFTO(DIR)
       FOR I=0 TO N-1
       FR(I)=FR(I)/N
       FI(I)=FI(I)/N
       NEXT I
```

```
REM   print the graph for 500 MHz results
      CALL SCALE
      CALL PLOT
30    IF INKEY$="" THEN 30
      SCREEN 0,0,0
      END
```

```
REM    FIG210.BAS
REM    A PROGRAM TO MODEL A BROADBAND CABLE SYSTEM
REM    TWO-TONE INTERMODULATION MODEL
REM    CARRIER F1 ELEVATED BY 10 DB INTO COMPRESSION
REM    THIS PROGRAM WAS USED TO CREATE FIGURE 2.10 IN THE TEXT
REM    ALL REQUIRED SUBROUTINES ARE LISTED IN PROGRAM "FIG207.BAS"
REM    (this program runs under the Microsoft QuickBASIC complier)
REM
REM    $DYNAMIC
       DIM FR(16383),FI(16383)
       DEFINT I-N
REM    assign constants
       NAME$="FIG210"
       PI=3.141592654
REM    10=>1024,11=>2048,12=>4096,13=>8192,14=>16384
       LN=14
       LM=2^(LN-10)
       N=2^LN
       NV2=N/2
       NM1=N-1
       HZ=PI/NV2
       DD=1.122^(10)
REM    assign test data
       FOR K=1 TO N
       I=K-1
REM    enter the rf carrier freq & levels
       FR=0
       FR=FR+.5*DD*SIN(I*HZ*110.00)
       FR=FR+.5*SIN(I*HZ*155.00)
REM    introduce the nonlinear characteristic
       DF=.80
       IF FR>1 THEN FR=FR^DF
       FR(I)=FR
       FI(I)=0
REM    adjust the spectral placement
       FR(I)=FR(I)*(-1)^I
       NEXT K
REM    call the FFT routine
       DIR=1.
       CALL FFTO(DIR)
       FOR I=0 TO N-1
       FR(I)=FR(I)/N
       FI(I)=FI(I)/N
       NEXT I
REM    print the graph for 500 MHz results
       CALL SCALE
       CALL PLOT
30     IF INKEY$="" THEN 30
       SCREEN 0,0,0
       END
```

```
REM   FIG211.BAS
REM   A PROGRAM TO MODEL A BROADBAND CABLE SYSTEM
REM   MULTIPLE TONE INTERMODULATION MODEL
REM   ALL CARRIERS ARE CLIPPED BY 3 DB
REM   THIS PROGRAM WAS USED TO CREATE FIGURE 2.11 IN THE TEXT
REM   ALL REQUIRED SUBROUTINES ARE LISTED IN PROGRAM "FIG207.BAS"
REM   (this program runs under the Microsoft QuickBASIC complier)
REM
REM   $DYNAMIC
      DIM FR(16383),FI(16383)
      DEFINT I-N
REM   assign constants
      NAME$="FIG211"
      PI=3.141592654
REM   10=>1024,11=>2048,12=>4096,13=>8192,14=>16384
      LN=14
      LM=2^(LN-10)
      N=2^LN
      NV2=N/2
      NM1=N-1
      HZ=PI/NV2
      DD=1.122^(3)
REM   assign test data
      FOR K=1 TO N
      I=K-1
REM   enter the rf carrier freq & levels
      FR=0
      FR=FR+SIN(I*HZ*175)+.178*SIN(I*HZ*180) :'CH 7
      FR=FR+SIN(I*HZ*289)+.178*SIN(I*HZ*294) :'CH V
      FR=FR+SIN(I*HZ*12)+.178*SIN(I*HZ*17)   :'CH T8
      FR=FR+SIN(I*HZ*36)+.178*SIN(I*HZ*41)   :'CH T12
      FR=FR+.316*SIN(I*HZ*84)+.316*SIN(I*HZ*277) :'SYTEK
      FR=FR+.178*SIN(I*HZ*75)+.178*SIN(I*HZ*268) :'UNGERMANN-BASS
      FR=FR*DD
REM   introduce the nonlinear characteristic
      DF=.80
      IF FR>3.97 THEN FR=3.97
      FR(I)=FR
      FI(I)=0
REM   adjust the spectral placement
      FR(I)=FR(I)*(-1)^I
      NEXT K
REM   call the FFT routine
      DIR=1.
      CALL FFTO(DIR)
      FOR I=0 TO N-1
      FR(I)=FR(I)/N
      FI(I)=FI(I)/N
      NEXT I
```

```
REM   print the graph for 500 MHz results
      CALL SCALE
      CALL PLOT
30    IF INKEY$="" THEN 30
      SCREEN 0,0,0
      END
```

```
REM     FIG212.BAS
REM     A PROGRAM TO MODEL A BROADBAND CABLE SYSTEM
REM     TWO-TONE INTERMODULATION MODEL
REM     BOTH CARRIERS ARE CLIPPED BY 3 DB
REM     THIS PROGRAM WAS USED TO CREATE FIGURE 2.12 IN THE TEXT
REM     ALL REQUIRED SUBROUTINES ARE LISTED IN PROGRAM "FIG207.BAS"
REM     (this program runs under the Microsoft QuickBASIC compiler)
REM
REM     $DYNAMIC
        DIM FR(16383),FI(16383)
        DEFINT I-N
REM     assign constants
        NAME$="FIG212"
        PI=3.141592654
REM     10->1024,11->2048,12->4096,13->8192,14->16384
        LN=14
        LM=2^(LN-10)
        N=2^LN
        NV2=N/2
        NM1=N-1
        HZ=PI/NV2
REM     assign test data
        FOR K=1 TO N
        I=K-1
REM     enter the rf carrier freq & levels
        FR=0
        FR=FR+SIN(I*HZ*110)
        FR=FR+SIN(I*HZ*155)
REM     introduce the nonlinear characteristic
        FR=FR*1.122^3
        IF FR>2 THEN FR=2
        FR(I)=FR
        FI(I)=0
REM     adjust the spectral placement
        FR(I)=FR(I)*(-1)^I
        NEXT K
REM     call the FFT routine
        DIR=1.
        CALL FFTO(DIR)
        FOR I=0 TO N-1
        FR(I)=FR(I)/N
        FI(I)=FI(I)/N
        NEXT I
REM     print the graph for 500 MHz results
        CALL SCALE
        CALL PLOT
30      IF INKEY$="" THEN 30
        SCREEN 0,0,0
        END
```

```
REM   FIG213.BAS
REM   A PROGRAM TO MODEL A BROADBAND CABLE SYSTEM
REM   MULTIPLE TONE INTERMODULATION MODEL
REM   ALL CARRIERS ARE SUBJECTED TO RECTIFICATION
REM   THIS PROGRAM WAS USED TO CREATE FIGURE 2.13 IN THE TEXT
REM   ALL REQUIRED SUBROUTINES ARE LISTED IN PROGRAM "FIG207.BAS"
REM   (this program runs under the Microsoft QuickBASIC complier)
REM
REM   $DYNAMIC
      DIM FR(16383),FI(16383)
      DEFINT I-N
REM   assign constants
      NAME$="FIG213"
      PI=3.141592654
REM   10=>1024,11=>2048,12=>4096,13=>8192,14=>16384
      LN=14
      LM=2^(LN-10)
      N=2^LN
      NV2=N/2
      NM1=N-1
      HZ=PI/NV2
REM   assign test data
      FOR K=1 TO N
      I=K-1
REM   enter the rf carrier freq & levels
      FR=0
      FR=FR+SIN(I*HZ*175)+.178*SIN(I*HZ*180) :'CH 7
      FR=FR+SIN(I*HZ*289)+.178*SIN(I*HZ*294) :'CH V
      FR=FR+SIN(I*HZ*12)+.178*SIN(I*HZ*17)   :'CH T8
      FR=FR+SIN(I*HZ*36)+.178*SIN(I*HZ*41)   :'CH T12
      FR=FR+.316*SIN(I*HZ*84)+.316*SIN(I*HZ*277) :'SYTEK
      FR=FR+.178*SIN(I*HZ*75)+.178*SIN(I*HZ*268) :'UNGERMANN-BASS
REM   introduce the nonlinear characteristic
      DF=.90
      IF FR>0 THEN FR=FR^DF
      FR(I)=FR
      FI(I)=0
REM   adjust the spectral placement
      FR(I)=FR(I)*(-1)^I
      NEXT K
REM   call the FFT routine
      DIR=1.
      CALL FFTO(DIR)
      FOR I=0 TO N-1
      FR(I)=FR(I)/N
      FI(I)=FI(I)/N
      NEXT I
```

```
REM   print the graph for 500 MHz results
      CALL SCALE
      CALL PLOT
30    IF INKEY$="" THEN 30
      SCREEN 0,0,0
      END
```

```
REM    FIG214.BAS
REM    A PROGRAM TO MODEL A BROADBAND CABLE SYSTEM
REM    TWO-TONE INTERMODULATION MODEL
REM    BOTH CARRIERS ARE SUBJECTED TO RECTIFICATION
REM    THIS PROGRAM WAS USED TO CREATE FIGURE 2.14 IN THE TEXT
REM    ALL REQUIRED SUBROUTINES ARE LISTED IN PROGRAM "FIG207.BAS"
REM    (this program runs under the Microsoft QuickBASIC complier)
REM

REM    $DYNAMIC
       DIM FR(16383),FI(16383)
       DEFINT I-N
REM    assign constants
       NAME$="FIG214"
       PI=3.141592654
REM    10=>1024,11=>2048,12=>4096,13=>8192,14=>16384
       LN=14
       LM=2^(LN-10)
       N=2^LN
       NV2=N/2
       NM1=N-1
       HZ=PI/NV2
REM    assign test data
       FOR K=1 TO N
       I=K-1
REM    enter the rf carrier freq & levels
       FR=0
       FR=FR+SIN(I*HZ*110)
       FR=FR+SIN(I*HZ*155)
REM    introduce the nonlinear characteristic
       DF=.90
       IF FR>0 THEN FR=FR^DF
       FR(I)=FR
       FI(I)=0
REM    adjust the spectral placement
       FR(I)=FR(I)*(-1)^I
       NEXT K
REM    call the FFT routine
       DIR=1.
       CALL FFTO(DIR)
       FOR I=0 TO N-1
       FR(I)=FR(I)/N
       FI(I)=FI(I)/N
       NEXT I
REM    print the graph for 500 MHz results
       CALL SCALE
       CALL PLOT
30     IF INKEY$="" THEN 30
       SCREEN 0,0,0
       END
```

```
REM   FIG215.BAS
REM   A PROGRAM TO SIMULATE THE EFFECTS OF INTERSYMBOL INTERFERENCE
REM   BY BANDPASS FILTERING THE SPECTRUM OF A DIGITAL SIGNAL
REM   THIS VERSION USES PROGRESSIVE FILTERING OF THE SPECTRUM
REM   THIS PROGRAM WAS USED TO CREATE FIGURE 2.15 IN THE TEXT
REM   (this program runs under the Microsoft QuickBASIC complier)
REM
REM   $DYNAMIC
      DIM FR(4096),FI(4096),GR(4096),GI(4096)
      DEFINT I-N
      SCREEN 2,0,0
      LINE (0,20)-(0,199)
      LINE (1,20)-(1,199)
      LINE (0,199)-(500,199)
      LINE (500,199)-(500,20)
      LINE (501,199)-(501,20)
      LINE (500,20)-(0,20)
REM   assign constants
      NAME$="FIG215"
      PI=3.141592654
      LN=12
      N=2^LN
      NV2=N/2
      NM1=N-1
      NB=500
REM   assign test data
      FOR I=1 TO N
      FR(I)=1
      FI(I)=0
      NEXT I
      DATA 0,1,2,1,0,1,2,1,0,1,0,1,0,1,2,2,2,1
      DATA 1,2,1,0,0,0,1,2,2,1,0,1,1,2,2,2,2,1,0,0,0,0
      NBIT=40
      FOR IB=1 TO NBIT
      READ LEVEL
      FOR I=41 TO 50
      K=I+10*IB
      FR(K)=LEVEL
      NEXT I
      NEXT IB
REM   plot the time domain function
      VP=50
      CALL PLOT
REM   adjust the spectral placement
      FOR I=1 TO N
      FR(I)=FR(I)*(-1)^I
      NEXT I
```

```
REM   call the FFT routine
      DIR=1.
      CALL FFT(DIR)
      FOR I=1 TO N
      FR(I)=FR(I)/N
      FI(I)=FI(I)/N
      NEXT I
      DIR=-1.
      FOR I=1 TO N
      GR(I)=FR(I)
      GI(I)=FI(I)
      NEXT I
REM   filter at first null F
      ML=1636
      MH=2460
      MS=824
      CALL SINFILTER
      CALL FFT(DIR)
REM   print the results
      VP=86
      CALL PLOT
      FOR I=1 TO N
      FR(I)=GR(I)
      FI(I)=GI(I)
      NEXT I
REM   filter at F/2
      ML=1842
      MH=2254
      MS=412
      CALL SINFILTER
      CALL FFT(DIR)
REM   print the results
      VP=122
      CALL PLOT
      FOR I=1 TO N
      FR(I)=GR(I)
      FI(I)=GI(I)
      NEXT I
REM   filter at F/4
      ML=1945
      MH=2151
      MS=206
      CALL SINFILTER
      CALL FFT(DIR)
```

```
REM   print the results
      VP=158
      CALL PLOT
      FOR I=1 TO N
      FR(I)=GR(I)
      FI(I)=GI(I)
      NEXT I
      CLOSE
REM   apply the Sytek IF filter characteristic
      CF=2048
      CALL SYTEKFILTER
      CALL FFT(DIR)
REM   print the results
      VP=194
      CALL PLOT
      LOCATE 1,1:PRINT NAME$
      DEF SEG=&HB800
      BSAVE NAME$+".PLT",0,&H4000
20    IF INKEY$="" THEN 20
      END
```

```
        SUB FFT(DIR) STATIC
REM     array FR is the real portion of the Fourier array
REM     array FI is the imaginary portion of the Fourier array
REM     DIR is a forward/inverse director (+ is forward, - is inverse)
        SHARED FR(),FI()
        SHARED PI,N,NV2,NM1,LN
        DEFINT I-N
        J=1
        FOR I=1 TO NM1
        IF I=>J THEN 1
        SWAP FR(J),FR(I)
        SWAP FI(J),FI(I)
1       K=NV2
2       IF K=>J THEN 3
        J=J-K
        K=K/2
        GOTO 2
3       J=J+K
        NEXT I
        FOR L=1 TO LN
        LE=2^L
        LE1=LE/2
        UR=1.0
        UI=0.0
        WR=COS(PI/LE1)
        WI=-DIR*SIN(PI/LE1)
        FOR J=1 TO LE1
        FOR I=J TO N STEP LE
        IP=I+LE1
        TR=FR(IP)*UR-FI(IP)*UI
        TI=FR(IP)*UI+UR*FI(IP)
        FR(IP)=FR(I)-TR
        FI(IP)=FI(I)-TI
        FR(I)=FR(I)+TR
        FI(I)=FI(I)+TI
        NEXT I
        TUR=UR*WR-UI*WI
        TUI=UR*WI+WR*UI
        UR=TUR
        UI=TUI
        NEXT J
        NEXT L
        END SUB
```

```
        SUB PLOT STATIC
REM     plots the graphs of the calculated functions
        SHARED FR(),FI()
        SHARED PI,NB,VP
        DEFINT I-N
        FMAX=0
        FOR I=1 TO NB
        FMAG=SQR(FR(I)^2+FI(I)^2)
        IF FMAX<FMAG THEN FMAX=FMAG
        NEXT I
        FMAX=25/FMAX
        FOR I=1 TO NB
        FMAG=(SQR(FR(I)^2+FI(I)^2))
        FMAG=VP-((SQR(FR(I)^2+FI(I)^2)))*FMAX
        IF I=1 THEN FOLD=FMAG
        LINE (I,FOLD)-(I,FMAG)
        FOLD=FMAG
        NEXT I
        END SUB
REM
        SUB SINFILTER STATIC
REM     applies a sinusoidal filter in the frequency domain
        SHARED FR(),FI()
        SHARED PI,N,ML,MS,MH
REM     set lower edge of spectrum to zero
        FOR I=1 TO ML
        FR(I)=0
        FI(I)=0
        NEXT I
REM     set upper edge of spectrum to zero
        FOR I=MH TO N
        FR(I)=0
        FI(I)=0
        NEXT I
REM     multiply passband by a sinusoidal weighting
        PI1=PI/MS
        FOR I=0 TO MS
        K=I+ML
        SI=SIN(I*PI1)
        FR(K)=FR(K)*SI
        FI(K)=FI(K)*SI
        NEXT I
        END SUB
```

```
      SUB SYTEKFILTER STATIC
REM   applies a model of the Sytek IF filter in the frequency domain
      SHARED FR(),FI()
      SHARED N,CF
      ML=CF-40
      MH=CF+40
REM   set lower edge of spectrum to zero
      FOR I=1 TO ML
      FR(I)=0
      FI(I)=0
      NEXT I
REM   set upper edge of spectrum to zero
      FOR I=MH TO N
      FR(I)=0
      FI(I)=0
      NEXT I
REM   multiply passband by Sytek weighting
      FOR I=1 TO 25
      FIL=1E-6 +(40000*I)
      K=ML-1+I
      FR(K)=FR(K)*FIL
      FI(K)=FI(K)*FIL
      K=MH+1-I
      FR(K)=FR(K)*FIL
      FI(K)=FI(K)*FIL
      NEXT I
      END SUB
```

```
REM   FIG216.BAS
REM   A PROGRAM TO SIMULATE THE EFFECTS OF INTERSYMBOL INTERFERENCE
REM   BY BANDPASS FILTERING THE SPECTRUM OF A DIGITAL SIGNAL
REM   THIS VERSION PLACES THE SYTEK FILTER AT ASSIGNED SUBCHANNELS
REM   WITHIN THE UNGERMANN-BASS SPECTRUM
REM   THIS PROGRAM WAS USED TO CREATE FIGURE 2.16 IN THE TEXT
REM   ALL REQUIRED SUBROUTINES ARE LISTED IN PROGRAM "FIG215.BAS"
REM   (this program runs under the Microsoft QuickBASIC complier)
REM
REM   $DYNAMIC
      DIM FR(4096),FI(4096),GR(4096),GI(4096)
      DEFINT I-N
      SCREEN 2,0,0
      LINE (0,20)-(0,199)
      LINE (1,20)-(1,199)
      LINE (0,199)-(500,199)
      LINE (500,199)-(500,20)
      LINE (501,199)-(501,20)
      LINE (500,20)-(0,20)
REM   assign constants
      NAME$="FIG216"
      PI=3.141592654
      LN=12
      N=2^LN
      NV2=N/2
      NM1=N-1
      NB=500
REM   assign test data
      FOR I=1 TO N
      FR(I)=1
      FI(I)=0
      NEXT I
      DATA 0,1,2,1,0,1,2,1,0,1,0,1,0,1,2,2,2,1
      DATA 1,2,1,0,0,0,1,2,2,1,0,1,1,2,2,2,2,1,0,0,0,0
      NBIT=40
      FOR IB=1 TO NBIT
      READ LEVEL
      FOR I=41 TO 50
      K=I+10*IB
      FR(K)=LEVEL
      NEXT I
      NEXT IB
REM   plot the time domain function
      VP=50
      CALL PLOT
REM   adjust the spectral placement
      FOR I=1 TO N
      FR(I)=FR(I)*(-1)^I
      NEXT I
```

```
REM   call the FFT routine
      DIR=1.
      CALL FFT(DIR)
      FOR I=1 TO N
      FR(I)=FR(I)/N
      FI(I)=FI(I)/N
      NEXT I
      DIR=-1.
REM   apply sin filter to simulate Ungermann-Bass spectrum
      ML=1636
      MH=2460
      MS=824
      CALL SINFILTER
      FOR I=1 TO N
      GR(I)=FR(I)
      GI(I)=FI(I)
      NEXT I
REM   filter on band edge
      CF=1636:'center at band edge
      CALL SYTEKFILTER
      CALL FFT(DIR)
REM   print the results
      VP=86
      CALL PLOT
      FOR I=1 TO N
      FR(I)=GR(I)
      FI(I)=GI(I)
      NEXT I
REM   filter on Ch. 9
      CF=1751:'center on Sytek Ch. 9
      CALL SYTEKFILTER
      CALL FFT(DIR)
REM   print the results
      VP=122
      CALL PLOT
      FOR I=1 TO N
      FR(I)=GR(I)
      FI(I)=GI(I)
      NEXT I
REM   filter on Ch. 12
      CF=1900:'center on Sytek Ch. 12
      CALL SYTEKFILTER
      CALL FFT(DIR)
REM   print the results
      VP=158
      CALL PLOT
      FOR I=1 TO N
      FR(I)=GR(I)
      FI(I)=GI(I)
      NEXT I
```

```
REM   filter on Ch. 16 (near center of band)
      CF=2097:'center on Sytek Ch. 16
      CALL SYTEKFILTER
      CALL FFT(DIR)
REM   print the results
      VP=194
      CALL PLOT
      LOCATE 1,1:PRINT NAME$
      DEF SEG = &HB800
      BSAVE NAME$+".PLT",0,&H4000
20    IF INKEY$="" THEN 20
      END
```

VITA

Richard I. Crutcher was born in Chapel Hill, Tennessee, on May 26, 1953. He attended Forrest High School and was graduated as Salutatorian of his class in May 1971. He entered Tennessee Technological University, Cookeville, and while working on his studies, participated in the cooperative education program with NASA in Huntsville, Alabama. He received his Bachelor of Science degree in Electrical Engineering in 1977.

After working a year for Teledyne Brown Engineering in Huntsville, Alabama, and performing graduate studies at Tennessee Technological University, he began his employment at the Oak Ridge National Laboratory in Oak Ridge, Tennessee. He commenced study toward a Master's degree in Electrical Engineering at the University of Tennessee, Knoxville, in Fall 1986. This degree was awarded in June 1988.

The author is a registered professional engineer in the state of Tennessee and holds a General Radiotelephone Operator License from the Federal Communications Commission. Mr. Crutcher is employed in the Instrumentation and Controls Division of Oak Ridge National Laboratory where he is involved in the design and development of analog and radio-frequency electronics.