

An All-Digital Automatic Gain Control

APPLICATION REPORT: SPRA081

Al Lovrich
Raj Chirayil
Digital Signal Processor Products
Semiconductor Group
Texas Instruments

Digital Signal Processing Solutions



IMPORTANT NOTICE

Texas Instruments (TI) reserves the right to make changes to its products or to discontinue any semiconductor product or service without notice, and advises its customers to obtain the latest version of relevant information to verify, before placing orders, that the information being relied on is current.

TI warrants performance of its semiconductor products and related software to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are utilized to the extent TI deems necessary to support this warranty. Specific testing of all parameters of each device is not necessarily performed, except those mandated by government requirements.

Certain application using semiconductor products may involve potential risks of death, personal injury, or severe property or environmental damage ("Critical Applications").

TI SEMICONDUCTOR PRODUCTS ARE NOT DESIGNED, INTENDED, AUTHORIZED, OR WARRANTED TO BE SUITABLE FOR USE IN LIFE-SUPPORT APPLICATIONS, DEVICES OR SYSTEMS OR OTHER CRITICAL APPLICATIONS.

Inclusion of TI products in such applications is understood to be fully at the risk of the customer. Use of TI products in such applications requires the written approval of an appropriate TI officer. Questions concerning potential risk applications should be directed to TI through a local SC sales office.

In order to minimize risks associated with the customer's applications, adequate design and operating safeguards should be provided by the customer to minimize inherent or procedural hazards.

TI assumes no liability for applications assistance, customer product design, software performance, or infringement of patents or services described herein. Nor does TI warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right of TI covering or relating to any combination, machine, or process in which such semiconductor products or services might be or are used.

TRADEMARKS

TI is a trademark of Texas Instruments Incorporated.

Other brands and names are the property of their respective owners.

CONTACT INFORMATION

US TMS320 HOTLINE	(281) 274-2320
US TMS320 FAX	(281) 274-2324
US TMS320 BBS	(281) 274-2323
US TMS320 email	dsph@ti.com

An All-Digital Automatic Gain Control

Abstract

This report describes an all-digital implementation of an AGC on a TMS320C17 DSP. The AGC is designed specifically for modem applications.

- ❑ The first section provides an overview of modem receiver structure and implementation.
- ❑ The second section discusses the AGC block diagram and the motivation for using an AGC in a modem receiver.
- ❑ The third section covers the AGC hardware and software implementation aspects on a TMS320C17 DSP.
- ❑ Appendix A provides QAM Signal Energy data.
- ❑ Appendix B gives an overview on Fractional Number Representation.



Product Support

World Wide Web

Our World Wide Web site at www.ti.com contains the most up to date product information, revisions, and additions. Users registering with TI&ME can build custom information pages and receive new product updates automatically via email.

Email

For technical issues or clarification on switching products, please send a detailed email to dsph@ti.com. Questions receive prompt attention and are usually answered within one business day.

One of the basic structural blocks of a modem receiver is the Automatic Gain Control (AGC). The AGC is an adaptive system that operates over a wide dynamic range while maintaining the output signal at a constant level. This is necessary for the proper operation of the carrier recovery and clock recovery algorithms of the modem receiver.

This application report describes an all-digital implementation of an AGC on a TMS320C17 Digital Signal Processor (DSP). The AGC is designed specifically for modem applications. The structure of this application report is as follows:

- The first section provides an overview of modem receiver structure and implementation.
- Section two discusses the AGC block diagram and the motivation for using an AGC in a modem receiver.
- The last section covers the AGC hardware and software implementation aspects on a TMS320C17 DSP.

Introduction

A modem (MODulator/DEModulator) is a device that modulates baseband signals at the transmitter and demodulates the received data at the receiver. To achieve full-duplex operation, frequency division multiplexing is employed, in which both modems simultaneously transmit and receive information over a single channel by dividing the telephone bandwidth into separate frequency bands: one for transmit with a carrier frequency of 1200 Hz and one for receive with a carrier frequency of 2400 Hz. A modem receiver consists of several functional blocks, which include answer/originate bandpass filters, AGC, demodulator, adaptive equalizer, clock recovery, carrier recovery, decision block, decoder, and descrambler.

In this report, we are concerned with the implementation of a DSP-based AGC for a V.22 bis modem product[1]. One of the basic structural blocks of a modem receiver is the AGC. The AGC is an adaptive system that operates over a wide dynamic range while maintaining the output signal at a constant level. The AGC is needed because several modules within the receiver use amplitude thresholds to make their decisions. These threshold levels must remain constant over the entire dynamic range of input signals, typically from -9 dbm to -43 dBm[2]. This is achieved through use of a software AGC, which multiplies the input signal with a gain factor, depending on the actual received signal level.

Modem Transmitter

The CCITT V.22 bis standard is a 2400-bps modem that uses Quadrature Amplitude Modulation (QAM) technique to transmit and receive data through the communications channel. This section presents an overview of QAM systems and the equations governing their operations.

In Quadrature Amplitude Modulation, the information is encoded as phase changes of the transmitted carrier and amplitude variations. With R denoting the amplitude and ϕ the phase change, the transmitted signal $s(n)$ is mathematically represented as

$$s(n) = R \cos(\omega_c n + \phi) \quad (1)$$

where ω_c is the carrier frequency. Simplifying (1) and substituting $I_n = R \cos(\phi)$ and $Q_n = -R \sin(\phi)$ into it results in (2); this is used to describe QAM modulation systems.

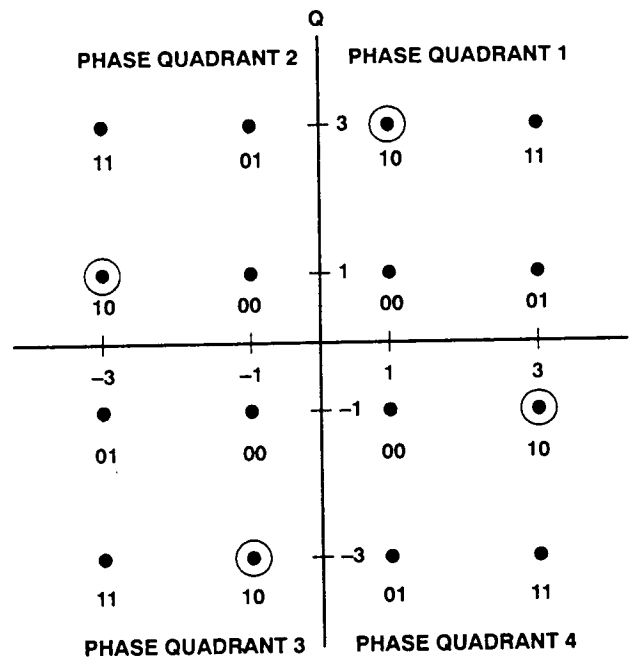
$$s(n) = I_n \cos(\omega_n) + Q_n \sin(\omega_n) \quad (2)$$

Transmission of a baseband sequence $\{I_n, Q_n\}$ is called *quadrature* transmission, with two carriers in phase quadrature to one another ($\cos \omega_c t$ and $\sin \omega_c t$) transmitted simultaneously over the same communications channel. Figure 1 shows a two-dimensional diagram of the signals of form (2) with the horizontal axis corresponding to the *in-phase* signal (I_n) and the vertical axis representing the *quadrature* signal (Q_n). These signal points are referred to as a 16-symbol QAM-signal constellation.

Each value of the $\{I_n, Q_n\}$ corresponds to one signaling element transmitted. The number of signaling elements per second is referred to as the baud rate. The *baud rate* is set by the CCITT V.22 bis recommendation to 600. By encoding four incoming bits (*quadbits*) in a single baud, transmission of 2400 bps is accomplished.

The encoding of the incoming data stream $d_s(n)$ into values of the sequence $\{I_n, Q_n\}$ is accomplished by the encoder. The encoder maps the first two bits of a quadbit as a phase quadrant change relative to the quadrant occupied by the preceding signal element. The last two bits of the quadbit define one of four signaling elements associated with the new quadrant[3].

Figure 1. V.22 bis Signal Constellation

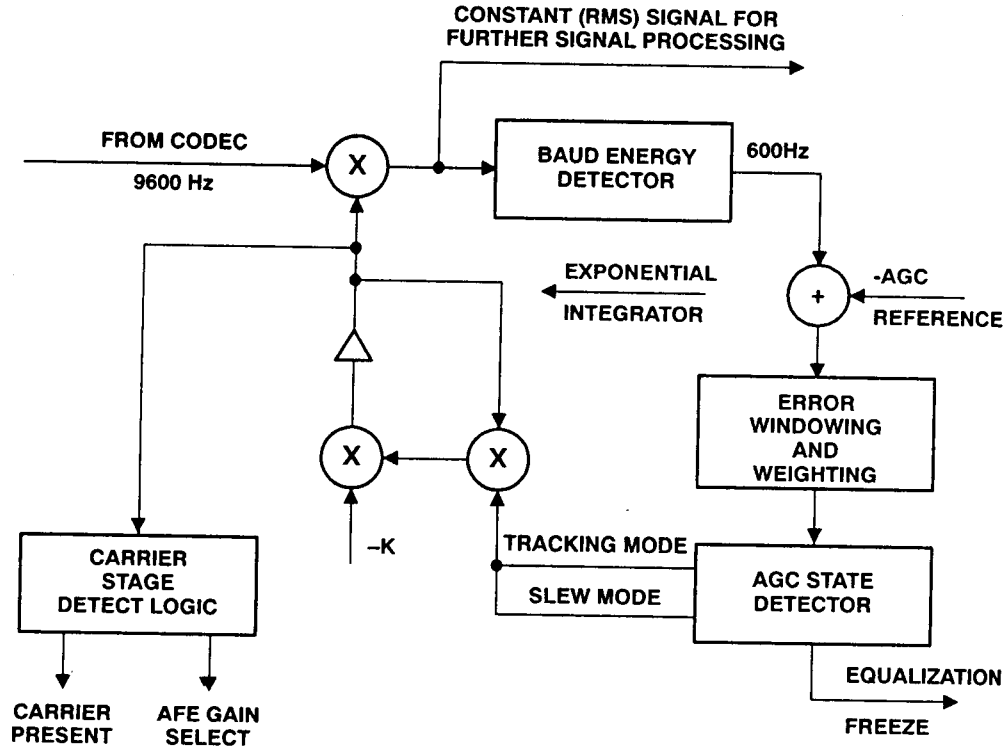


The AGC Algorithm

The AGC circuit is a closed-loop regulating system that maintains the output level of an amplifier at a constant level, even though the input signal may vary substantially. The AGC modeling and design techniques based on linear system design have been studied in detail[4]. The global stability of AGC loops assures the designer that the overall loop will stay stable under considerable weaker conditions if the proper design rules are followed[5].

Figure 2 is a block diagram of the modem automatic gain control. The AGC algorithm is partitioned into tasks performed once per sampling interval, and tasks performed once per baud interval. The sampling rate for the overall system is the designer's choice as long as it satisfies the Nyquist's criterion. A widely used sampling rate for the communications channel is 8 kHz. In the system in Figure 2, the sampling rate is chosen to be an integer multiple of the baud rate. Therefore, a sampling rate of 9.6 kHz is selected. This value is divisible by the master crystal frequency of 18.432 MHz.

Figure 2. Modem AGC Block Diagram



Baud Energy Detector

In Figure 2, every incoming linearized PCM sample is multiplied by the AGC gain factor. The result is available to the modem receiver for further signal processing. It is also used to update the baud energy detector. The energy of a baud interval is computed according to

$$E = \sum x_n^2 \quad (3)$$

where x_n represents the incoming samples. The accumulated baud energy is then compared against a reference level, which depends on the modulation scheme. This comparison is necessary to compute the AGC loop error signal. It is this error that the AGC is trying to minimize.

The QAM transmitted signal shown in (2) can be rewritten, taking waveform shaping into account as follows

$$s(t) = \sum I_n g(t-nT) \cos \omega_c t + \sum Q_n g(t-nT) \sin \omega_c t \quad (4)$$

where $\omega_c = 2\pi f_c$, where f_c = carrier frequency
 $g(t)$ = shaping waveform
 T = sampling interval
 I_n, Q_n = data symbols

AGC Reference Energy

The signal energy for a particular constellation point (I_n, Q_n) is given by (see Appendix A)

$$E_n = 1/2 (I_n^2 + Q_n^2) \quad (5)$$

The energy reference level is chosen to be

$$E_{ref} = E \{ E_n \} \quad (6)$$

where $E\{ \}$ denotes the expectation operation. The V.22 bis modem standard requires the transmitter to scramble the incoming digital sequence from the DTE and descramble the decoded data in the receiver[2,3]. The use of scrambler in the modem transmitter effectively randomizes the data and avoids data-dependent patterns in the transmitted sequence. This allows the constellation point sequences to be modeled as a random sequence, with each point having an equal probability of occurrence of $E\{(I_n, Q_n)\} = 1/N$. Therefore, (6) can be written as

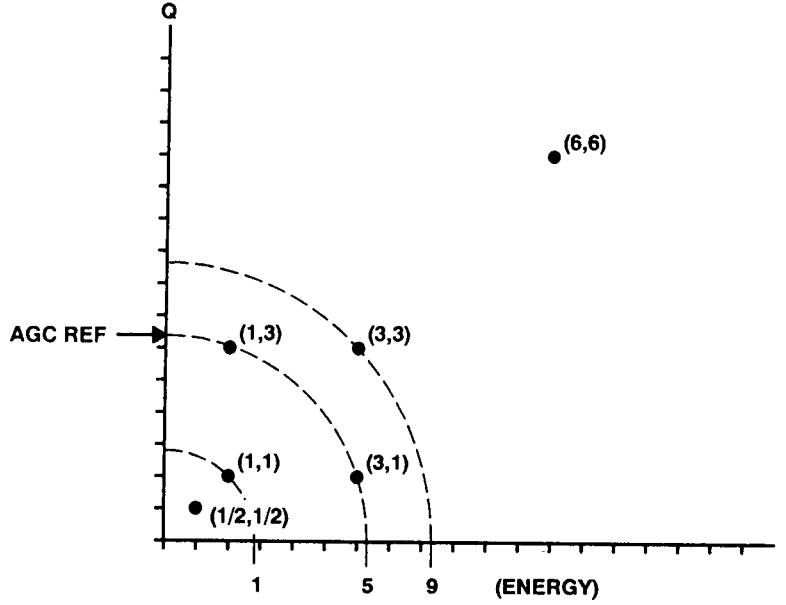
$$E_{ref} = \sum_{n=1}^N 1/N (E_n) \quad (7)$$

Figure 3 shows a portion of the signal constellation diagram of a V.22 bis modem.

Applying (7) to all 16 constellation points results in

$$\begin{aligned} E_{ref} &= 1/16 \{ 4 [(1^2 + 3^2) + 1/2 (1^2 + 1^2) + 1/2 (3^2 + 3^2)] \} \\ &= 1/16 \{ 4 [(10) + (1) + (9)] \} \\ &= 5 \end{aligned} \quad (8)$$

Figure 3. Signal Energy Constellation Diagram



In Figure 3, constellation points (3,3) and (1,1) with respective energy contents of 9 and 1 lie outside the reference level of 5. A window function is then necessary so that the AGC does not treat these energy variations around the nominal energy as distortions induced by the communication channel.

Therefore, the AGC should apply corrections when the incoming signal level is outside the interval (1,9)(see Figure 3). Such implementation, however, neglects the effects of intersymbol interference (ISI). ISI arises in systems whenever pulses are transmitted in a band-limited channel. In such channels, pulses tend not to die out immediately, and the tail from one pulse interferes with the next pulse. ISI-related effects are more easily shown when constant amplitude modulation techniques, such as DPSK, are considered. In a DPSK modem receiver, the received signal exhibits gain variations, that are entirely due to ISI. Since the modem equalizer compensates for ISI, the AGC should not act upon ISI-related signal-level variations, because this would introduce noise into the modem receiver and degrade the overall performance.

The received signal $r(t)$ at the input of the receiver is the convolution of the channel impulse response $h(t)$ with the transmitted symbols x_j in

$$r(t) = \sum_j x_j h(t - jT) + \mu(t) \quad (9)$$

where $\mu(t)$ is the additive white Gaussian noise. For the effects of ISI to be seen, the received signal must be sampled at the instant $t_0 + kT$ with t_0 incorporating the sampler phase and delay effects.

$$r(t_0 + kT) = x_k h(t_0) + \sum_{j \neq k} x_j h(t_0 + kT - jT) + \mu(t_0 + kt) \quad (10)$$

The first term of the right-hand side of (10) is the desired signal and is used to determine the transmitted symbol, while the middle term is ISI, which arises from the neighboring symbols [6]. With x_k , a constant amplitude sequence, the middle term in (10) results in received signal amplitude variations. Thus, the AGC design must incorporate an energy window around the energy reference level as defined by x_k 's.

DSP Implementation

Hardware

This section describes the hardware requirements of the modem. The modem hardware consists of the following functional blocks:

- 1) Host Interface
- 2) DSP
- 3) Controller
- 4) Controller-DSP Interface
- 5) Analog Front-End
- 6) Telephone Line Interface

For the purpose of understanding the operation of the Automatic Gain Control (AGC), the discussion is limited to only the analog front end.

Modem Analog Front End

The function of the analog front end (AFE) in the modem is to convert the analog signals received on the telephone line to digital data that can be processed by a digital signal processing device, in this case the TMS320C17. Depending on the modem standard that is implemented, the modem AFE could further assist the DSP by preventing as many of the unwanted signals as possible from being received by the DSP. This reduces the signal conditioning and preprocessing required by the DSP, which, in turn, reduces the computational requirement.

In the implementation described here, the modem AFE performs the bandpass filtering, a single-step gain stage, and the A/D-D/A conversions. Although the modem hardware also includes the two-to-four wire conversion and the proper telephone line interface and impedance matching, it will not be considered in this discussion.

Split-band Filtering

In Frequency Division Multiplexing (FDM) modems, the originating and answering stations use different carrier frequencies to transmit data[2]. For V.22 bis modems, the originating modem transmits data using a 1200-Hz carrier and receives signals from the remote modem at 2400 Hz. Since these signals are carried over the two-wire Public Switched Telephone Network (PSTN) for a full duplex communication, both signals are present in the telephone line simultaneously. For a modem to prevent its transmitted signal from interfering with its received signal, it must eliminate its own transmit signal at its receiver. Since the two modems use separate carrier frequencies to

transmit, this task becomes relatively easy. It is done by bandpass filtering the received signal with the passband filter being centered at the transmit carrier frequency of the remote modem.

This implementation uses a commercially available modem filter that has special modes to allow call-progress signal monitoring. This filter must provide adequate adjacent channel rejection while maintaining linear phase. The filter must operate over the entire dynamic range required by the modem, typically from 0 dBm to -43 dBm. For better Signal-to-Noise Ratio (SNR) and linear phase, it is desirable not to operate the filter and the Analog-to-Digital converter at very low signal levels. If signals are weak, an external gain stage (turned on/off under software control) in the receive signal path easily accomplishes this goal.

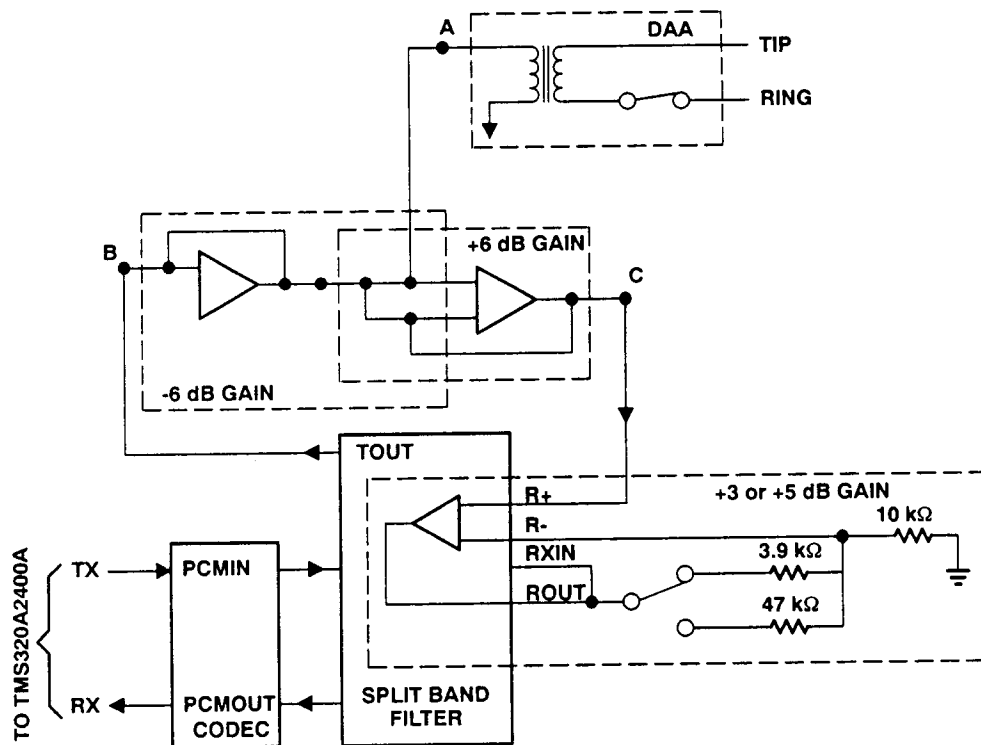
Hardware Gain Control

The hardware gain switch is implemented by changing the gain in the analog input buffer to the filter. When the average signal energy falls below -28 dBm, the DSP sets a status line to the modem controller. The controller, in turn, switches on a different resistor in the feedback circuit of the op-amp, increasing the gain by 12 dB. This switching is normally done only once during call initialization. However, if the connection starts with low-level signals and later the signals become stronger due to change in line impedance, the DSP resets this status line to the controller. The modem controller then turns off the external gain stage.

When the modem received signal is actually at the threshold level, it is possible that the external gain could frequently be turned on and off by slight changes in signal level. To prevent this, a 4-dB hysteresis has been established between external gain On and Off. This means the external gain will be turned On when the average signal level is less than -24 dBm and will be turned Off when the level is more than -28 dBm. Figure 4 shows the AFE schematic of the modem.

	LINE (dBm)	AFE GAIN (dB)	CODEC (dBm)
Rx level	-12	0	-9
	-24	0	-21
	-25	12	-10
	-43	12	-28

Figure 4. Modem AFE Schematic



Codec Interface

The TMS320A2400A features hardware companding logic to interface directly to a μ -law codec[1]. The SCLK output provides the master clock frequency for the codec, and the FR provides the transmit and receive framing signal to the codec. Since the modem algorithm uses a 9.6-kHz sampling frequency, the codec must complete one A/D,D/A conversion at this rate.

The DSP serial port control register was programmed to provide an SCLK which is generated by dividing the DSP's input clock by ten. Thus, using an 18.432-MHz crystal as the DSP's clock input, a 1.8432-MHz SCLK was generated. The TCM29C19 uses an internal divide ratio of 192 to generate the 9.6-kHz sampling rate.

Software

The previous section provided a brief overview of the hardware design issues associated with the AGC for a V.22 bis modem. DSP implementation issues are the focus throughout the rest of this report. All values are represented in decimal format unless otherwise noted. Data values in a digital system are not integers, but they must be manipulated as such on an integer processor. Appendix B provides an overview of fractional number representation on a two's-complement fixed-point device.

We choose to represent the signal within the AGC loop in S4.11 format. Recall that the $\{I_n, Q_n\}$ sequence can assume any value from the sequence $\{\pm 1, \pm 3\}$. This means that the sequence is bound in the ± 3 range. We use three bits to represent the values in the given range, while the rest of the 12 bits can be treated as the fractional part that accommodates noise. Allocating an extra bit to the $\{I_n, Q_n\}$ sequence fully represents the RMS signal and allows for some gain hit.

For QAM signals, experimentation has shown that the ratio of peak signal to RMS signal is approximately 3 to 1. The maximum peak signal that can be represented using S4.11 notation is 16 (see Appendix B); therefore, 16 represents the peak value a QAM signal can attain using this notation. The RMS_{max} is hence 5.33, which corresponds to approximately 14.5 dB ($20 \log 5.33$). We design the system to work with a 10-dB gain hit. It follows that the AGC should maintain the signal level at approximately 4.5 dB or 1.69 RMS level. The constant level of 1.69 RMS represented in S4.11 format is 3461.12. The AGC loop maintains an average squared level of 2.86, or $(1.69)^2$, per sample. Therefore, to determine the average baud energy, the sample energy must be multiplied by 16. The resultant value (45.8) is represented in S10.5 format (corresponding to 1466 (05BAh) in S15.0 format), the actual value used in the implementation (see Appendix E for the code listing).

As shown in the previous section, the reference energy for a V.22 bis modem is 5. This corresponds to the energy level of the constellation points (1,3) and (3,1), shown in Figure 3. Hence it is possible to map the average baud energy of 5 into 45.8. Extending the mapping to the other energy levels results in the following:

Average Baud Energy		S10.5 Format	S15.0 Format
1	maps into	9.16	292
5	maps into	45.8	1466
9	maps into	82.4	2632

Error Windowing and Weighting

In the previous section, the need was established for an energy window around the nominal baud energy level to compensate for the effects of intersymbol interference. The AGC is not designed to, and should not be expected to, compensate for ISI. The equalizer in the modem receiver is designed for this purpose [6]. Experimental window values of 1320 and 950 were chosen for QAM and DPSK modes of operation, respectively.

The windowed error signal must be weighted appropriately to provide an approximate one-to-one relationship between the positive and negative energy errors. In Figure 3, the disparity between the positive and negative errors can be observed. Assume that the received points are (6,6) and (0.5,0.5). The QAM signal energy can be calculated as

$$E_{QAM} = 1/2 (I_n^2 + Q_n^2) \quad (11)$$

Therefore, the energy values of the received points are 36 and 0.25, respectively. When these energy values are represented in S10.5 (10552 and 73, respectively) and the deviation from the nominal energy level of 1466 is calculated, full scale error values of 9086 and -1393, respectively, are obtained. This indicates a nonlinear relationship between the received constellation points signal energy with respect to the nominal baud energy level. It is important to determine the weighting

factor to provide a parity between positive and negative errors while the AGC operates in the steady state or tracking mode. Appendix D provides a Fortran program to determine the best value for the expansion ratio of negative and positive energy values.

AGC State Detector

The AGC always operates in one of two modes:

- Slew – (fast tracking mode) AGC uses a large step size to track the signal.
- Tracking – AGC adjusts the signal level by adjusting the gain factor via an exponential integrator loop.

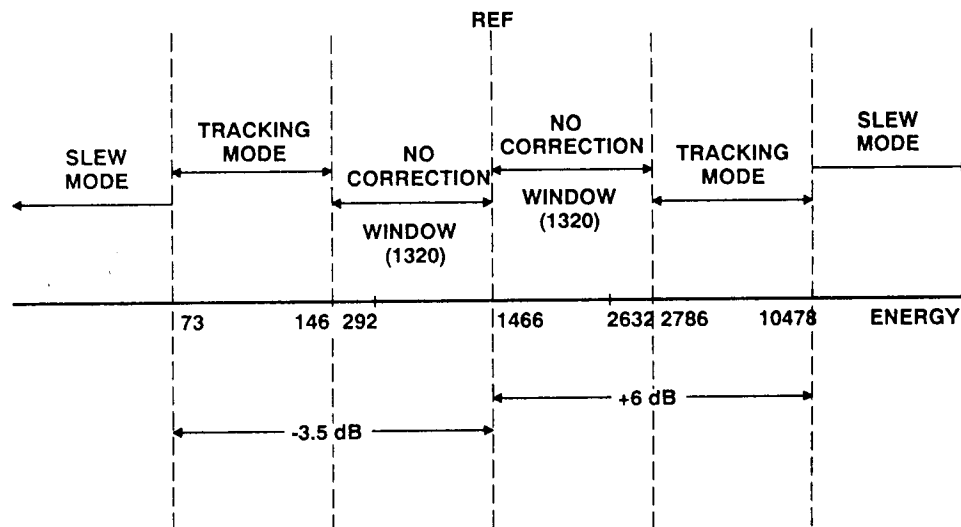
It is important to design the AGC to ignore relatively small gain changes on the telephone line. Otherwise, the AGC loop responds to the smallest variation in the signal level by switching to the slew mode. In this application, the AGC is designed to simply track the incoming signal when the received signal level varies by not more than ± 6 dB from the window values. These levels are calculated as follows:

$$10 \log(x/2632) = +6 \text{ dB} \rightarrow x = 10478 \quad (12)$$

$$10 \log(x/292) = -6 \text{ dB} \rightarrow x = 73 \quad (13)$$

As long as the incoming signal stays within these boundaries, the AGC simply adjusts the gain factor; otherwise, it will switch to the slew mode. Once the AGC determines that the error signal is within the tracking mode boundary, it switches back to the slow tracking mode as shown in 5.

Figure 5. AGC Operating Modes



Appendix C provides a FORTRAN program that determines the best weighting factor for a given QAM signal range. A weighting factor of 2 provided the approximate one-to-one relation-

ship. Since DPSK signals do not have amplitude variations, a value of 1 was chosen for the weighting factor when the modem operates in the V.22/Bell 212A mode.

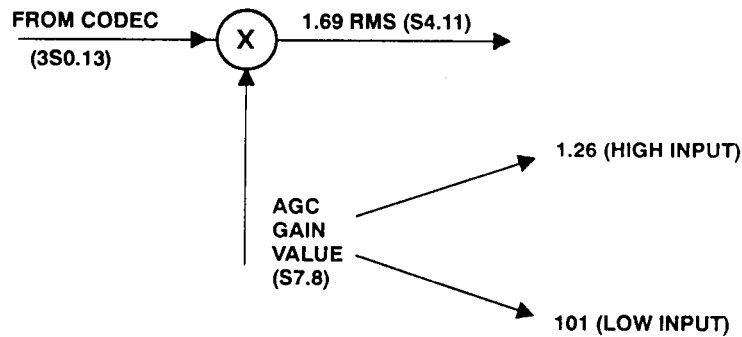
An upper and lower boundary for the AGC gain value must be determined. The V.22bis standard[3] requires the modem to operate at a signal level of -43 dBm. Therefore, the AGC is designed to work from the 0-dBm signal level to -50 dBm.

The DSP2400 contains a DSP-activated 12-dB gain switch. Therefore, our design should really have to cover only the range of 0 dBm to -38 dBm levels. The maximum codec output value is 1FFEh (8190 decimal) because the codec output is converted from 8-bit log value to 13-bit two's-complement value. When this value is saved in a data memory location of the TMS320C17 DSP, the number is sign-extended and is represented in 3S0.13 format. The RMS_{max} is therefore 2730, which corresponds to a signal level of 0 dBm in our system. The minimum acceptable signal level from the codec corresponding to the -38-dBm level is computed as follows:

$$\begin{aligned} -38 &= 20 \log (RMS_{min} / 2730) \\ RMS_{min} &= 34.4 \end{aligned} \quad (14)$$

Given the maximum and minimum codec output values and the constant RMS output, it follows that $\alpha_{min} = 1.26$ and $\alpha_{max} = 101$ as shown in Figure 6.

Figure 6. AGC Gain Value Computation



The gain value requires 7 bits to represent; therefore, the S7.8 format is used to represent the α values.

Exponential Integrator Loop

When the total baud energy stays within the window limits, the AGC is in the tracking mode and simply compensates for the changes in the signal levels by adjusting the gain factor appropriately. The gain factor is computed and updated via an exponential integrator loop. The exponential integrator loop implements the following function:

$$\alpha_{n+1} = \alpha_n \times (1 - Ke) \quad (15)$$

where the constant K determines the speed of convergence of the AGC closed loop. In our implementation, K is set to 1/2. This value corresponds to step sizes of ± 6 dB when the AGC is in the

slew mode. The error signal is in S0.15 format while α_n is in S7.8 format with the multiplication result in 2S7.23 format. When the upper half of the accumulator (ACCH) is saved with a left shift, the result is in S7.8 format. A further multiplication by 0.5 is necessary before carrying out the subtraction operation. Note that a divide by 2 is equivalent to a right shift, which cancels out the effect of the previous left shift. Therefore, saving ACCH with no shift accomplishes multiplication by K as shown in Appendix E.

The AGC is designed to declare carrier present when signal levels greater than -43 dBm appear at the input of the receiver. The response time for tone detection depends on the AGC design. The AGC uses a constant that is subtracted from a hysteresis counter, and presence of energy is declared when the counter underflows. It takes 9 bauds for the energy to be detected, corresponding to a response time of 15 ms.

Conclusion

This application report has presented design and implementation techniques for an all-digital automatic gain control. The AGC has been implemented on a TMS320C17 digital signal processor as part of a commercial modem product (DSP2400). The approach of using a programmable processor resulted in minimal hardware configuration with excellent performance. The DSP implementation allows you to fine tune the AGC for your particular modem design, regardless of the modulation technique used.

Acknowledgements

The author wishes to acknowledge the contribution of Technekron Communications Systems and George Troullinos of Texas Instruments. This report is based on their work.

References

- 1) *DSP2400 Modem User's Guide*, Texas Instruments, 1987.
- 2) Troullinos, G., et al, *Theory and Implementation of a Splitband Modem Using the TMS32010* (literature number SPRA013), Texas Instruments, 1986.
- 3) Recommendation V.22 bis, "2400 bits per second duplex modem using the frequency division technique standardized for use on the general switched telephone network and on point-to-point 2-wire leased telephone-type circuits," *CCITT Redbook*, Volume III, 1984.
- 4) Mercy, D.V., "A Review of Automatic Gain Control Theory," *The Radio and Electronic Engineer*, Volume 51, Number 11/12, November/December 1981.
- 5) Green, D.N., "Global Stability Analysis of Automatic Gain Control Circuits," *IEEE Transactions on Systems and Circuits*, Volume CAS-30, Number 2, February 1983.
- 6) Falconer, D.D., "Jointly Adaptive Equalization and Carrier Recovery in Two-Dimensional Digital Communication Systems," *Bell System Technical Journal*, Volume 55, Number 3, March 1976.
- 7) Antoniou, A., *Digital Filters: Analysis and Design*, John Wiley & Sons, 1986.
- 8) Lovrich, A., et al, "An All Digital Automatic Gain Control," *Proceedings of ICASSP 88*, Pages 1734–1737.

Appendix A

QAM Signal Energy

The general form of a QAM signal is written as

$$\begin{aligned} s(t) &= R(t) \cos[\omega_c t + \phi(t)] \\ &= I_n \cos \omega_c t + Q_n \sin \omega_c t \end{aligned} \quad (16)$$

The energy in a signal $s(t)$ is defined as

$$E_{QAM} = \int_{-\infty}^{\infty} s^2(t) dt \quad (17)$$

Substituting (16) into (17) results in

$$\begin{aligned} E_{QAM} &= \int_0^T s^2(t) dt \\ &= \frac{1}{2\pi} \int_0^{2\pi} (I_n^2 \cos^2 \omega_c t + Q_n^2 \sin^2 \omega_c t + 2I_n Q_n \sin \omega_c t \cos \omega_c t) dt \\ &= \frac{1}{2\pi} \int_0^{2\pi} 1/2 [I_n^2 (1 + \cos 2\omega_c t)] dt + \frac{1}{2\pi} \int_0^{2\pi} 1/2 [Q_n^2 (1 - \cos 2\omega_c t)] dt \\ &\quad + \frac{1}{2\pi} \int_0^{2\pi} I_n Q_n \sin 2\omega_c t dt \end{aligned} \quad (18)$$

When the three terms in (18) are integrated, the sine and cosine terms drop out since the average energy of sinusoidal signals is zero. Therefore, (18) simplifies to

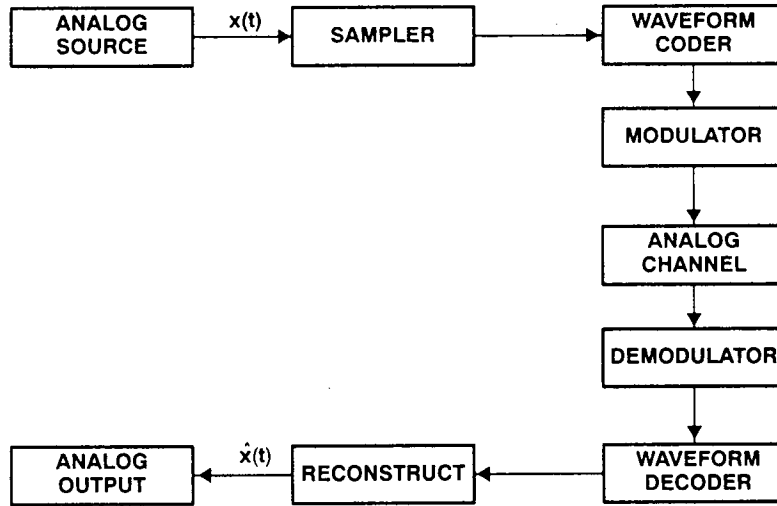
$$E_{QAM} = 1/2 (I_n^2 + Q_n^2) \quad (19)$$

Appendix B

Fractional Number Representation Overview

A typical digital communication system is shown in Figure 7. Two blocks (marked as waveform coder and waveform decoder) are of interest. These blocks are collectively referred to as a codec, especially when both coder and decoder are implemented on a single device. An example is the TCM29C13 PCM codec, which consists of an amplitude quantizer and binary codeword generator.

Figure 7. A Typical Communication Channel



The quantized data represent instantaneous values of a continuous-time signal in digital form. On the TMS320C17, these data values are represented in two's-complement arithmetic[7]. The binary representation of a two's-complement value is as follows:

$$A = a_0 + \sum_{i=1}^{15} a_i 2^{-i} \quad (20)$$

Consider that the incoming samples are coming from a 16-bit linear ADC. The data coming out of the ADC consist of a sign bit at the most significant location, followed by the binary point. This information can be represented in Q15 format or, alternately, S0.15 format. This translates into the following upperbound and lowerbound limits with increments of 2^{-15} (0.00003051):

$$\begin{aligned} (2^{15} - 1) / 2^{15} &= 0.99996948 \\ -2^{15} / 2^{15} &= -1 \end{aligned} \quad (21)$$

If two Q15 (S0.15) numbers are multiplied, the result is a number in Q30 (SS0.30) format. When the Q30 number resides in the 32-bit accumulator of the TMS320C17, the binary point fol-

lows the second most-significant bit. Assuming that the output of the encoder section is also Q15 format, the Q30 number must be adjusted by left-shifting by one while maintaining the most-significant 16 bits of the result. This is accomplished with a sach y,1. This instruction shifts the Q30 (SS0.30) number to the left by one and, following the shift, stores the upper 16 bits of the accumulator. The y value is in Q15 (S0.15) format.

The S notation is used consistently throughout this application report. The following table should assist you with the conversion between Q notations, S notations, and equivalent decimal representations.

Table 1. S Notation, Q Notation, and Decimal Conversion Information

Q Notation	S Notation	Decimal Equivalent
Q15	S0.15	-1 N≤ 0.9999695
Q14	S1.14	-2 N≤ 1.9999390
Q13	S2.13	-4 N≤ 3.9998779
Q12	S3.12	-8 N≤ 7.9997559
Q11	S4.11	-16 N≤ 15.9995117
Q10	S5.10	-32 N≤ 31.9990234
Q9	S6.9	-64 N≤ 63.9980469
Q8	S7.8	-128 N≤ 127.9960938
Q7	S8.7	-256 N≤ 255.9921875
Q6	S9.6	-512 N≤ 511.9804375
Q5	S10.5	-1024 N≤ 1023.96875
Q4	S11.4	-2048 N≤ 2047.9375
Q3	S12.3	-4096 N≤ 4096.875
Q2	S13.2	-8192 N≤ 8191.75
Q1	S14.1	-16384 N≤ 16383.5
Q0	S15.0	-32768 N≤ 32767

Appendix C

The following is a Fortran program listing that creates a table of AGC gain values and its relation to the input signal strength. The table also includes the corresponding peak input signal level and its RMS equivalent.

```

994,997

```

```

c This program determines the values of dcm signal levels in a dcm system
c Double Precision Peak, rms, alpha, dba.
c
c - Peak is the peak signal input to the receiver side.
c
c - rms is the rms signal input to the receiver, where in a dcm system is
c equal to on third of the peak value.
c
c - Alpha is the gain value.
c
c In this ADC design, the max code input is actually +2.2 dba (equivalent to
c 8190 peak.

```

```

open (1,'r') = 'com.dat', status = 'new'

```

```

write (1,8)
format (5x, '000',15x, 'peak',10x, 'rms',17x, 'alpha')

```

```

write (1,9)
format (5x, '15x',15x, 'max',10x, 'min',17x, 'mean')
dba = -27.1
max = 2.1

```

```

999 if (dba.gt. max) goto 1000
dba = dba + 0.1
peak = 8190. * 110 ** ((dba - max) / 20.1)
rms = peak / 3.
alpha = 346.12 / rms

```

```

write (1,10) dba,peak,rms,alpha
format (f10.1,10x,f10.4,10x,f10.4,10x,f10.2)
goto 999

```

```

c
1000 stop
end

```

dba	Peak	rms	Alpha
-27.0	290.3922	96.8441	35.73
-26.9	293.9571	97.9857	35.32
-26.8	297.3609	99.1203	34.92
-26.7	300.6042	100.2481	34.52
-26.6	304.2873	101.4291	34.12
-26.5	307.8108	102.6036	33.73
-26.4	311.3751	103.7917	33.35
-26.3	314.9807	104.9926	32.97
-26.2	318.6280	106.2093	32.59
-26.1	322.3175	107.4392	32.21
-26.0	326.0498	108.6833	31.85
-25.9	329.8252	109.9417	31.48
-25.8	333.6444	111.2148	31.12
-25.7	337.5079	112.5026	30.76
-25.6	341.4160	113.8053	30.41
-25.5	345.3694	115.1231	30.06
-25.4	349.3686	116.4562	29.72
-25.3	353.4141	117.8047	29.38
-25.2	357.5065	119.1688	29.04
-25.1	361.6462	120.5487	28.71
-25.0	365.8338	121.9446	28.38
-24.9	370.0700	123.3567	28.06
-24.8	374.3532	124.7851	27.74
-24.7	378.6900	126.2300	27.42
-24.6	383.0751	127.6917	27.11
-24.5	387.5109	129.1703	26.80
-24.4	391.9980	130.6660	26.49
-24.3	396.5372	132.1791	26.19
-24.2	401.1288	133.7096	25.89
-24.1	405.7737	135.2579	25.59
-24.0	410.4723	136.8241	25.30
-23.9	415.2254	138.4085	25.01
-23.8	420.0335	140.0112	24.72
-23.7	424.8972	141.6324	24.44
-23.6	429.8173	143.2724	24.16
-23.5	434.7943	144.9314	23.88
-23.4	439.8290	146.6097	23.61
-23.3	444.9220	148.3073	23.34
-23.2	450.0740	150.0247	23.07
-23.1	455.2856	151.7619	22.81
-23.0	460.5575	153.5192	22.55
-22.9	465.8905	155.2968	22.29
-22.8	471.2853	157.0951	22.03
-22.7	476.7425	158.9142	21.78
-22.6	482.2629	160.7543	21.53
-22.5	487.8473	162.6158	21.28
-22.4	493.4963	164.4988	21.04
-22.3	499.2107	166.4036	20.80
-22.2	504.9913	168.3304	20.56
-22.1	510.8388	170.2796	20.33
-22.0	516.7540	172.2513	20.09
-21.9	522.7378	174.2459	19.86

-21.8	328.7908	176.2636	19.64	-16.4	984.6545	328.2162	10.55
-21.7	334.9139	178.3046	19.41	-16.3	996.0563	332.0188	10.42
-21.6	341.1079	180.3693	19.19	-16.2	1007.3901	335.8634	10.31
-21.5	347.3736	182.4579	18.97	-16.1	1019.2574	339.7525	10.19
-21.4	353.7119	184.5706	18.75	-16.0	1031.0599	343.6866	10.07
-21.3	360.1236	186.7079	18.54	-15.9	1042.9990	347.6663	9.96
-21.2	366.6095	188.8698	18.33	-15.8	1055.0764	351.6921	9.84
-21.1	373.1706	191.0569	18.12	-15.7	1067.2926	355.7645	9.73
-21.0	379.8076	193.2692	17.91	-15.6	1079.6522	359.8841	9.62
-20.9	386.5214	195.5071	17.70	-15.5	1092.1540	364.0513	9.51
-20.8	393.3130	197.7710	17.50	-15.4	1104.8906	368.2669	9.40
-20.7	600.1853	200.0611	17.30	-15.3	1117.9936	372.5312	9.29
-20.6	607.1331	202.3777	17.10	-15.2	1130.3347	376.8449	9.18
-20.5	614.1633	204.7211	16.91	-15.1	1143.6577	381.2086	9.08
-20.4	621.2750	207.0917	16.71	-15.0	1156.8462	385.6227	8.98
-20.3	628.4690	209.4897	16.52	-14.9	1170.2441	390.0880	8.87
-20.2	635.7444	211.9155	16.33	-14.8	1183.8151	394.6050	8.77
-20.1	643.1080	214.3693	16.15	-14.7	1197.5231	399.1744	8.67
-20.0	650.5598	216.8516	15.96	-14.6	1211.3877	403.7966	8.57
-19.9	658.0079	219.3626	15.78	-14.5	1225.4170	408.4723	8.47
-19.8	665.7082	221.9027	15.60	-14.4	1239.6066	413.2022	8.38
-19.7	673.4167	224.4722	15.42	-14.3	1253.9666	417.9869	8.28
-19.6	681.2185	227.0715	15.24	-14.2	1268.4808	422.8269	8.19
-19.5	689.1026	229.7009	15.07	-14.1	1283.1691	427.7230	8.09
-19.4	697.0820	232.3607	14.90	-14.0	1298.0275	432.6758	8.00
-19.3	705.1539	235.0513	14.72	-13.9	1313.0579	437.6860	7.91
-19.2	713.3192	237.7731	14.56	-13.8	1328.2624	442.7541	7.82
-19.1	721.5790	240.5263	14.39	-13.7	1343.6430	447.8810	7.73
-19.0	729.9365	243.3115	14.23	-13.6	1359.2016	453.0672	7.64
-18.9	738.3867	246.1289	14.06	-13.5	1374.9405	458.3135	7.55
-18.8	746.9369	248.9790	13.90	-13.4	1390.8615	463.6205	7.47
-18.7	755.5860	251.8620	13.74	-13.3	1406.9669	468.9890	7.38
-18.6	764.3352	254.7794	13.58	-13.2	1423.2599	474.4196	7.30
-18.5	773.1858	257.7286	13.43	-13.1	1439.7394	479.9131	7.21
-18.4	782.1389	260.7130	13.28	-13.0	1456.4108	485.4703	7.13
-18.3	791.1956	263.7319	13.12	-12.9	1473.2753	491.0918	7.05
-18.2	800.3573	266.7858	12.97	-12.8	1490.3250	496.7783	6.97
-18.1	809.6250	269.8750	12.82	-12.7	1507.5922	502.5307	6.89
-18.0	819.0000	273.0000	12.68	-12.6	1525.0493	508.3498	6.81
-17.9	828.4855	276.1612	12.53	-12.5	1542.7066	514.2362	6.73
-17.8	838.0769	279.3590	12.39	-12.4	1560.5723	520.1908	6.65
-17.7	847.7814	282.5938	12.25	-12.3	1578.6429	526.2143	6.58
-17.6	857.5983	285.8661	12.11	-12.2	1596.9227	532.3076	6.50
-17.5	867.5288	289.1763	11.97	-12.1	1615.4142	538.4714	6.43
-17.4	877.5743	292.5248	11.83	-12.0	1634.1198	544.7046	6.35
-17.3	887.7361	295.9120	11.70	-11.9	1653.0420	551.0140	6.28
-17.2	898.0156	299.3385	11.56	-11.8	1672.1833	557.3944	6.21
-17.1	908.4141	302.8047	11.43	-11.7	1691.5463	563.8488	6.14
-17.0	918.9331	306.3110	11.30	-11.6	1711.1335	570.3778	6.07
-16.9	929.5728	309.8579	11.17	-11.5	1730.9475	576.9825	6.00
-16.8	940.3378	313.4459	11.04	-11.4	1750.9909	583.6636	5.93
-16.7	951.2264	317.0755	10.92	-11.3	1771.2664	590.4221	5.86
-16.6	962.2411	320.7470	10.79	-11.2	1791.7767	597.2699	5.80
-16.5	973.3833	324.4611	10.67	-11.1	1812.5245	604.1748	5.73

-11.0	1833.5126	611.1709	5.46	-5.5	3453.4943	1151.2314	3.01
-10.9	1854.7437	618.2979	5.40	-5.4	3492.4462	1164.5621	2.97
-10.8	1876.2204	625.4049	5.33	-5.3	3534.1412	1178.0471	2.94
-10.7	1897.9462	632.4467	5.47	-5.2	3575.0446	1191.6882	2.90
-10.6	1919.9224	639.9745	5.41	-5.1	3616.1619	1205.4873	2.87
-10.5	1942.1350	647.3850	5.35	-5.0	3658.3386	1219.4462	2.84
-10.4	1964.6441	654.8814	5.29	-4.9	3700.7602	1233.5657	2.81
-10.3	1987.3976	662.4445	5.22	-4.8	3743.5523	1247.8508	2.77
-10.2	2010.4066	670.1355	5.16	-4.7	3786.9005	1262.3002	2.74
-10.1	2033.6860	677.8953	5.11	-4.6	3830.7908	1276.9169	2.71
-10.0	2057.2250	685.7450	5.05	-4.5	3875.1088	1291.7029	2.68
-9.9	2081.0566	693.6853	4.99	-4.4	3919.9804	1306.6601	2.65
-9.8	2105.1541	701.7180	4.93	-4.3	3965.3717	1321.7966	2.62
-9.7	2129.5307	709.8436	4.88	-4.2	4011.2885	1337.0962	2.59
-9.6	2154.1895	718.0632	4.82	-4.1	4057.7370	1352.5790	2.56
-9.5	2179.1338	726.3779	4.76	-4.0	4104.7234	1368.2411	2.53
-9.4	2204.3670	734.7890	4.71	-3.9	4152.2539	1384.0846	2.50
-9.3	2229.8923	743.2974	4.66	-3.8	4200.3347	1400.1116	2.47
-9.2	2255.7133	751.9044	4.60	-3.7	4248.9723	1416.3241	2.44
-9.1	2281.8332	760.6111	4.55	-3.6	4298.1731	1432.7244	2.42
-9.0	2308.2556	769.4185	4.50	-3.5	4347.9436	1449.3145	2.39
-8.9	2334.9839	778.3260	4.45	-3.4	4398.2904	1466.0968	2.36
-8.8	2362.0218	787.3406	4.40	-3.3	4449.2202	1483.0794	2.33
-8.7	2389.3727	796.4576	4.35	-3.2	4500.7397	1500.2466	2.31
-8.6	2417.0403	805.6801	4.30	-3.1	4552.8559	1517.6186	2.28
-8.5	2445.0283	815.0094	4.25	-3.0	4605.5754	1535.1918	2.25
-8.4	2473.3404	824.4468	4.20	-2.9	4658.9055	1552.9685	2.23
-8.3	2501.9819	833.9935	4.15	-2.8	4712.8531	1570.9510	2.20
-8.2	2530.9519	843.6506	4.10	-2.7	4767.4253	1589.1418	2.18
-8.1	2560.2590	853.4197	4.06	-2.6	4822.6295	1607.5422	2.15
-8.0	2589.9054	863.3018	4.01	-2.5	4878.4729	1626.1576	2.13
-7.9	2619.8921	873.2964	3.96	-2.4	4934.9630	1644.9877	2.10
-7.8	2650.2220	883.4107	3.92	-2.3	4992.1072	1664.0357	2.08
-7.7	2680.9203	893.6401	3.87	-2.2	5049.9131	1683.3044	2.06
-7.6	2711.9639	903.9880	3.83	-2.1	5108.3883	1702.7961	2.03
-7.5	2743.3669	914.4556	3.78	-2.0	5167.5406	1722.5135	2.01
-7.4	2775.1336	925.0445	3.74	-1.9	5227.3779	1742.4593	1.99
-7.3	2807.2681	935.7560	3.70	-1.8	5287.9081	1762.6360	1.96
-7.2	2839.7748	946.5916	3.66	-1.7	5349.1392	1783.0444	1.94
-7.1	2872.6578	957.5526	3.61	-1.6	5411.0793	1803.6931	1.92
-7.0	2905.9216	968.6405	3.57	-1.5	5473.7367	1824.5789	1.90
-6.9	2939.5706	979.8569	3.53	-1.4	5537.1176	1845.7065	1.88
-6.8	2973.6092	991.2031	3.49	-1.3	5601.2364	1867.0788	1.85
-6.7	3008.0420	1002.6807	3.45	-1.2	5666.0957	1888.6966	1.83
-6.6	3042.8735	1014.2912	3.41	-1.1	5731.7060	1910.5687	1.81
-6.5	3078.1083	1026.0361	3.37	-1.0	5798.0760	1932.6720	1.79
-6.4	3113.7531	1037.9170	3.33	-0.9	5865.2145	1955.0715	1.77
-6.3	3149.8067	1049.9356	3.30	-0.8	5933.1305	1977.7102	1.75
-6.2	3186.2797	1062.0932	3.26	-0.7	6001.8329	2000.6110	1.73
-6.1	3223.1677	1074.4026	3.18	-0.6	6071.3309	2023.7770	1.71
-6.0	3260.4825	1086.8626	3.15	-0.5	6141.6336	2047.2122	1.69
-5.9	3298.2323	1099.4752	3.11	-0.4	6212.7504	2070.9168	1.67
-5.8	3336.4445	1112.1462	3.11	-0.3	6284.6966	2094.8969	1.65
-5.7	3375.0787	1125.0262	3.08	-0.2	6357.4639	2119.1546	1.63
-5.6	3414.1602	1138.0834	3.04				

-0.1	6431.0799	2143.6923	1.41
0.0	6305.5483	2168.5161	1.40
0.1	6380.8790	2193.6263	1.38
0.2	6657.0819	2219.0273	1.36
0.3	6734.1673	2244.7224	1.34
0.4	6812.1653	2270.7131	1.32
0.5	6891.0262	2297.0087	1.31
0.6	6970.8206	2323.6049	1.49
0.7	7051.5389	2350.5130	1.47
0.8	7133.1718	2377.7306	1.46
0.9	7215.7903	2405.2634	1.44
1.0	7299.3452	2433.1150	1.42
1.1	7383.8676	2461.2872	1.41
1.2	7469.3488	2489.7896	1.39
1.3	7555.8600	2518.6200	1.37
1.4	7643.3528	2547.7843	1.36
1.5	7731.8586	2577.2862	1.34
1.6	7821.3893	2607.1298	1.33
1.7	7911.9567	2637.3189	1.31
1.8	8003.5729	2667.8576	1.30
1.9	8096.2499	2698.7500	1.28
2.0	8190.0000	2730.0000	1.27

Appendix D

Appendix D provides a Fortran program that calculates an optimal value for the expansion ratio of negative and positive energy values, subject to some constraints (maximum signal levels). The program searches expansion ratios with their corresponding error values up to a maximum value defined by the user. The value that produces the least error is chosen as the optimal value. In this implementation, the tracking mode window is 6 dB for positive errors and at least 3.5 dBs wide for negative errors. The program, however, calculates the expansion window in 6-dB range. Error values are calculated using no-worse windows data. The index value for positive and negative errors correspond to the actual signal level in tenths of dBs.


```

      alterr = 292.4 * float(itr) * ( 1. - ( 10. ** (dlnegy / 10. )))
      write (1,3) alterr
      format (1x, 'Maximum energy level is ',f20.4)
      write (1,4) alterr
      format (1x, 'Minimum energy level is ',f20.4)
c
c      Output the N value
c
c      510      write(1,7) itr, binsz
c      7      format(1x,'N =',i3,' with the corresponding error of ',f20.4)
c
      end

```

Appendix E

[illegible]


```

; 20055 afe gain
;
;
;      lacc      07fh
;      and      stnd
;      sac1     stnd
;      lacc      00h
;      sac1     gn
;      ret
;
; 20056 hysteresis counter
;
;      decr      hysteresis counter
;
; 20057
;      dv      4d121      ; clear overflow bit
;
; 20058
;      zelh     hyst      ; hysteresis counter
;      subh     tws5      ; tws5 = 1927 = 32768/15
;      sac1     hyst
;
; 20059
;      in case of overflow declare loss of energy detect
;
;      dv      4d102
;      ret
;
; 20060
;      lacc      00fh
;      and      stnd
;      sac1     stnd
;      ret
;
; 20061
;      following lines are executed if afe gain is high but no energy detect.
;      check if alpha 21.28 (i.e. receive level <45.5 dbm) and increment
;      hysteresis counter if it is, otherwise, exit.
;
; 20062
;      lacc      thres2      ; 21.28 in s7.8
;      tbitr     tws0
;      lacc      tws0
;      sub       alpha
;      blz       20063
;
; 20063
;      alpha 21.28 = increment hyst. counter
;
; 20064
;      dv      4d101      ; clear overflow bit
;
; 20065
;      zelh     hyst
;      addh     tws5      ; tws5 contains inc. 40f
;      sac1     hyst
;
; 20066
;      detect bit stnd(63) = 1.
;
;      dv      4d104      ; in case of overflow set energy
;      ret

```

```

; 20067
;      lacc      00e16
;      or       stnd
;      sac1     stnd
;      ret
;
; 20068
;      if afe gain stage is bypassed, check level of alpha
;
; 20069
;      lacc      thres5
;      tbitr     tws0
;      lacc      tws0
;      sub       alpha
;      bpc       20070
;
; 20071
;      if alpha thres5 (20.09 in s7.8) then two afe gain stages used bit on.
;
;      lacc      0000h
;      or       stnd
;      sac1     stnd
;      lacc      0100h
;      sac1     gn
;
; 20072
;      ret
;
; 20073
;      routine for switching the afe on/off
;
; 20074
;      Zero band energy register
;
;      switch
;      zacc      0000h
;      sac1     0000h
;      lacc      0100h      ; mask off unwanted bits
;      and       gn
;      bz        20075
;
; 20075
;      check if the gain should be on
;
;      lacc      07fh      ; mask off the afe on bit
;      and       gn
;      sub       0000h      ; decrement the counter
;      bz        20076
;
; 20076
;      gn      ; save gn value
;      lacc      0100h      ; load the afe on bit
;      or       gn
;      sac1     gn
;      gn      ; restore afe on bit
;      ret

```

.....