DESIGN AND IMPLEMENTATION OF A PRACTICAL FLEX™ PAGING DECODER

by

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(ABSTRACT)

The Motorola Inc. paging protocol FLEX is discussed. The design and construction of a FLEX paging protocol decoder is discussed in detail. It proposes a decoding solution that includes a radio frequency (RF) receiver and a decoder board. The RF receiver will be briefly discussed. The decoder design is the main focus of this thesis as it transforms the RF frequency modulated (FM) data from the receiver and converts it to FLEX data words. The decoder is designed to handle bit sampling, bit clock synchronization, FLEX packet detection, and FLEX data word collection. The FLEX data words are then sent by the decoder to an external computer through a serial link for bit processing and storage. A FLEX transmitter will send randomly generated data so that a bit error rate (BER) calculation can be made at a PC. Each receiver's noise power and noise bandwidth will be measured so that noise spectral density may be calculated. A complete measurement set-up will be shown on how these noise measurements are made. The BER at a known power level is recorded. This enables E_b/N_o curves to be generated so that results of the decoding algorithm may be compared. This is performed on two different receivers.

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I would also like to thank MPRG who gave me my first taste of research when I was an undergraduate in 1989. I saw the program grow up to become a nationally recognized research group, and I feel proud to say that I was apart of it.

Lastly, I would like to express my deep love to my wife, Ann, and my family for whose support was needed to complete this long journey.

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Chapter 1

1. Introduction

The demand and growth in portable communications have forced new technologies to be developed. In the paging industry, the drive to new technology is due to the enormous growth and the limitation of current paging protocols. PageNet, the largest paging company in the U.S., has been forced to operate two nationwide paging frequencies[Wal 94]. The cost of adding a new frequency is great. Paging operators are looking for ways to put more data on the same frequency without reducing the coverage area, i.e. to increase system capacity. The way to increase system capability is to increase the amount of information transmitting in a given time. The first logical way to do this is to increase the data rate. POCSAG, an acronym for the Post Office Code Standardisation Advisory Group, is today's most prominent paging protocol. The fastest data rate that POCSAG can operate at is 2400 bits per second (bps) within the 12.5 kHz paging spectrum. The reason for this limitation is the classic time bandwidth problem. The energy of signal is related by the product of time and bandwidth so to increase the data rate in the same bandwidth causes a reduction in the energy of the signal. Increasing the data rate is not the only way to improve a system's capacity, another way is to improve the protocol efficiency so that less overhead information and more paging information is sent. POCSAG sends a long preamble to alert the pagers and many synchronization words which reduces the protocol's efficiency. Another concern that the paging operators have is missed pages. With increased data rates and the use of pagers in mobile applications, paging receivers are more susceptible to frequency selective fading. POCSAG has little fading protection in the protocol.

Motorola Inc. has developed a new paging protocol called FLEX™ [1] to address these concerns. Paging operators are looking at FLEX because it is a faster data rate system that allows more users within the same bandwidth. FLEX can operate at 6400 bps with bandwidth efficiency similar to POCSAG 2400. FLEX is also a more protocol efficient paging standard that does not have much overhead information. It also has fading tolerance through data interleaving. The system was designed for flexibility with standard Alpha, Numeric, and Tone pages but also allows for broadcast messages, direct binary messages, and other expandable features. The latest protocols from Motorola Paging Division is the release of it's new two-way paging technologies ReFLEX25™, ReFLEX50™, and InFLEXion™.[2] All of these build on the original FLEX protocol.

This thesis will discuss the design and construction of a FLEX paging protocol decoder. It proposes a decoding solution that includes a radio frequency (RF) receiver and a decoder board. The RF receiver will be discussed. The decoder design is the main focus of this thesis as it transforms the RF frequency modulated (FM) data from the receiver and converts it to FLEX data words. The decoder is designed to handle bit sampling, bit clock synchronization, FLEX packet detection, and FLEX data word collection. The FLEX data words are then sent by the decoder to an external computer through a serial link for bit processing and storage.

The receiver and decoder have been implemented in a commercial paging receiver product by Grayson Wireless. The 929 MHz to 932 MHz Paging Receiver (Grayson Part Number GMR120) is the RF receiver that the decoder needs to operate. The Paging Decoder (Grayson Part Number GMD200) is a paging decoder that can decode POCSAG, FLEX, GOLAY, and NEC. This thesis details the FLEX decoding portion of the GMD200 and the decoding of the other standards can be logically related since FLEX is the most difficult. The performance of the decoder design is measured using the Wireless Measurement System (Grayson Part Number GMM1000) equipped with three GMR120 and three GMD200. A HP8648A Signal Generator with the FLEX encoder option is used as the signal source. The GMM1000 is a measurement

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[1] FLEX is a registered trademark of Motorola, Inc.
[2] ReFLEX25, ReFLEX50, and InFLEXion are registered trademarks of Motorola, Inc.

mainframe that allows up to four pairs of receivers and decoders to communicate with a PC through a high speed serial port.

Chapter 2

2. FLEX Protocol

2.1 Overview of FLEX Protocol

The FLEX format is a high-speed paging protocol developed by Motorola Paging Products Group. FLEX is a multiple data rate paging protocol that can operate at a data rate up to 6400 bits per second (bps). The most common paging standard in the U.S. is Post Office Code Standardisation Advisory Group (POCSAG) that can operate at a binary data rate up to 2400 bps [Ste 96a]. FLEX uses 4-level frequency shift keying and an increased data rate that still operates in the 12.5 kHz bandwidth allocated by the FCC in the 929 MHz to 932 MHz band. With many nationwide paging providers reaching capacity with their POCSAG paging system, FLEX is a logical alternative since it offers 2.67 times more data than POCSAG (6400 bps compared to 2400 bps) for a given frequency. The FLEX protocol was designed to operate on the same frequency with existing POCSAG paging traffic. Each paging standard shares the air time.

FLEX is a synchronous protocol which means that all paging transmitters and receivers operate at the same time. The FLEX protocol requires that all receivers keep time within 5 μsec of the paging transmitter. The synchronous protocol improves channel efficiency and extends pager battery life. In POCSAG and other asynchronous paging standards, a preamble is transmitted for a length of time to guarantee that all pagers with that asynchronous protocol can "wake-up" or lock to the signal. The preamble wastes air time and forces pagers to keep their receiver circuits energized until a synchronization word is detected. Thus an asynchronous paging protocol is less efficient than a synchronous paging protocol at the same data rate because time spent

transmitting a preamble in an asynchronous protocol can be time used to transmit revenue generating data. The FLEX pager uses its low power CMOS circuit to keep time and only during its time slot does it power on the receiver for a short time to search for a synchronization word. The synchronous FLEX paging data is organized so that GPS clock accuracy can be used at the transmitter. [Wal 94]

2.2 FLEX Data Rate and Modulation

FLEX can operate at three data rates: 1600 bits per second (bps), 3200 bps, and 6400 bps. The modulation used is both two level frequency shift keying (2-FSK) and four level frequency shift keying (4-FSK). The 6400 bps FLEX is sent with 4-FSK, the 3200 bps can be sent either 2-FSK or 4-FSK, and the 1600 bps is always sent using 2-FSK. Thus there are only two baud rates in FLEX: 1600 baud and 3200 baud, where the number of bits in a symbol can be one or two. [Wal 94]

The frequency deviation for FLEX is 4.8 kHz for 2-FSK and 1.6 kHz and 4.8 kHz deviation for 4-FSK. Figure 2-1 shows a sample bit waveform and associated deviation for FLEX 2-FSK. A frequency above the center frequency (at +4.8 kHz) is a symbol 1 and below center frequency (at -4.8 kHz) is a symbol 0. For 2-FSK, there is one bit per symbol, so the symbol is the bit.
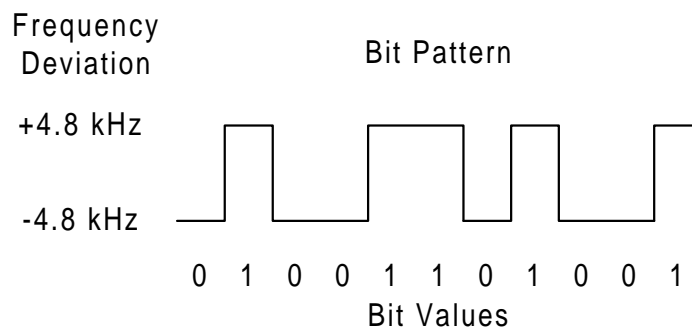
Figure 2-1 FLEX 2-FSK bit pattern with frequency deviation

The 4-FSK data is transmitted using a Gray-code [Cou 90] which means that the difference between any two adjacent levels or symbols can only have a one bit difference. The reason for this code is so that if a frequency deviation is close to the boundary and it's decoded to the wrong symbol only one bit will be wrong. The symbol order from -4.8 kHz to +4.8 kHz is 00, 01, 11, 10. Figure 2-2 displays a sample bit pattern with the appropriate symbol for FLEX 4-FSK. Also included is the corresponding frequency deviation. The difference between any adjacent symbols is 3.2 kHz.
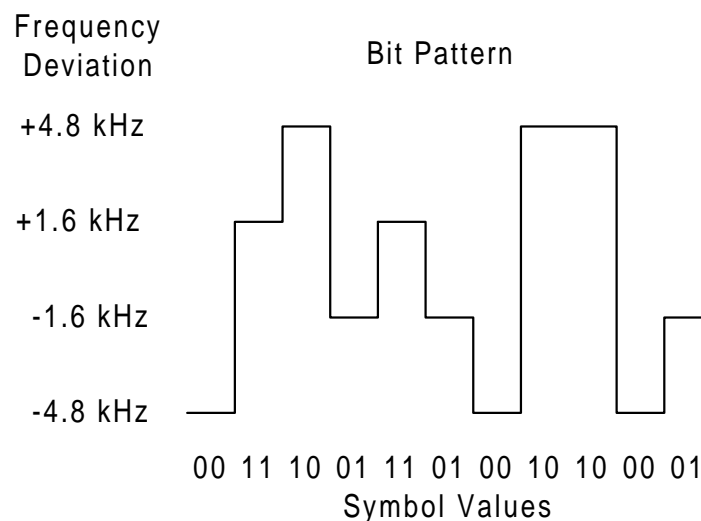
Figure 2-2 FLEX 4-FSK bit pattern with frequency deviation

2.3 FLEX Data Format

Figure 2-3 shows how the FLEX data is organized from cycles to frames. One hour contains 15 cycles. Cycles are numbered 0 to 14. Each cycle is 4 minutes long and contains 128 frames. Frames are number 0 to 127. Each frame is 1.875 seconds long. The frame is the smallest part of information that can be sent, but every frame in every cycle does not need to be transmitted. Although to keep all the FLEX pagers synchronized, every pager must receive one frame every 4 minutes. This "tickling" of the pagers keeps their clocks synchronized and allows them to "wake-up" at the appropriate time. Thus the minimum amount of FLEX activity requires a

FLEX pager to receive the same numbered frame within two consecutive cycles. For example, if cycle 0 frame 30 is transmitted, then the next frame that must be transmitted is cycle 1 frame 30. NOTE: The first release of Motorola FLEX pager, the PRO ENCORE, required that one frame be received every two minutes. This requires a minimum of two frames a cycle separated by 64 frames.

```
       |←———————— 15 Cycles = 1 Hour ————————→|
       ┌─────────┬─────────┬────┐    ┌────┬───────────┐
       │ Cycle 0 │ Cycle 1 │  ⧸ │    │ ⧸  │  Cycle 14 │
       └─────────┴─────────┴────┘    └────┴───────────┘


       |←———————— 128 Frames = 4 Minutes ————————→|
       ┌─────────┬─────────┬────┐    ┌────┬───────────┐
       │ Frame 0 │ Frame 1 │  ⧸ │    │ ⧸  │ Frames 127│
       └─────────┴─────────┴────┘    └────┴───────────┘


       |←— 1.875 Seconds —→|
```
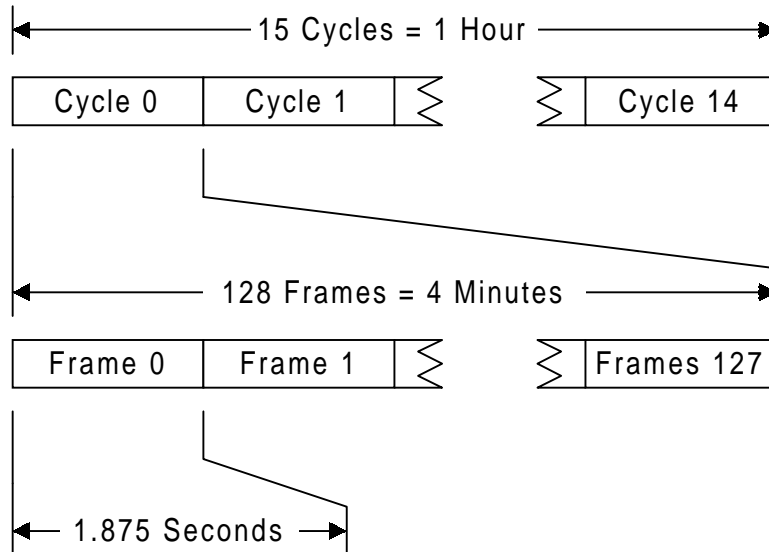
Figure 2-3 FLEX data organized in cycles and frames

The pager and paging terminal are set up to begin receiving and transmitting one frame out of every 2^x consecutive frames, where x can be 0 to 7. Thus when x is 0, continuous FLEX data frames are received. When x is 7, there is one frame received out of every 128 frames, and it is the same numbered frame. For example, if frame number 0 is received and frame numbers 1 through 127 are not received and frame number 0 of the next cycle is received, then x is 7. This example is the minimum amount of FLEX activity required so that a pager will remain synchronized.

2.3.1 Frame Format

The format of each frame is shown in Figure 2-4 [Ste 96b]. Each frame contains a synchronization period (Sync) of 115 ms and then 11 blocks of data with each block having a duration of 160 ms. Blocks are numbered 0 to 10.
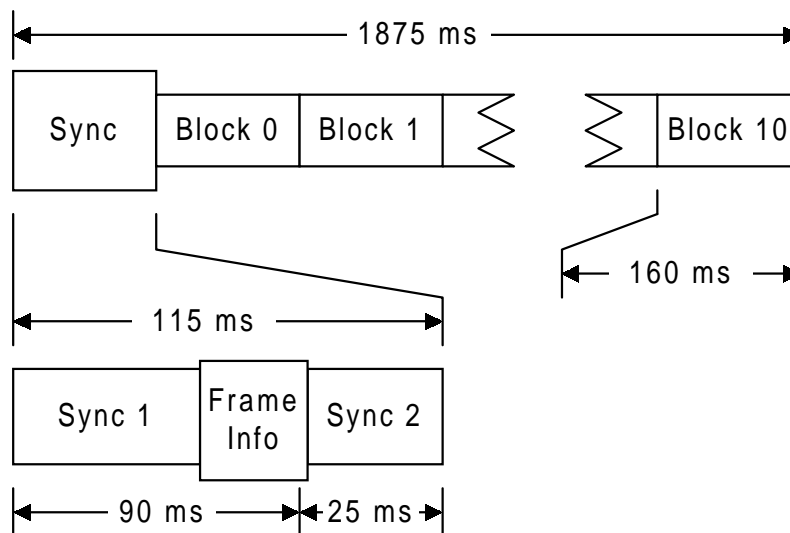
Figure 2-4 Frame format

The synchronization period contains two synchronization periods. The first synchronization period (Sync1 and Frame Info) is always sent at 1600 bps. Due to the proprietary nature of the FLEX protocol, the exact format of Sync1, Frame Info, and Sync2 cannot be discussed. Only important facts about each one will be discussed here so that a complete overview of the protocol can be given. Sync1 contains two 32-bit synchronization words that are separated by 16 dotting bits. These words are unique and identify the baud rate (1600 or 3200) and the modulation type (2-FSK or 4-FSK) of Sync2 and the data blocks. The frame information which is between Sync1 and Sync2 identifies the current frame number and cycle number. The total number of bits in Sync1 and Frame Info are 144 bits @ 1600 bps which is 90 ms in duration. Following Frame Info is the second synchronization period (Sync 2) which is 25 ms long. This synchronization is designed to train the receiver and decoder to the new modulation and baud rate.

2.3.2 Block Interleaving

Each block contains 8, 16, or 32 codewords of data for 1600 bps, 3200 bps, or 6400 bps, respectively. Each codeword is 32 bits long and contains information and parity bits. The structure of these codewords will be discussed in the next section. This section only discusses how the bits in the codewords are interleaved before transmission. The interleaving process is performed such that the first data bit in all the codewords are transmitted first, then the second data bit in all the codewords are transmitted, and this process continues until the 32nd data bit in all the codewords are transmitted. Figure 2-5 is the block interleaving for 1600 bps data and illustrates the order the bits are transmitted. The 32-bit codewords are arranged in rows and the bits are transmitted column by column. Each column requires 5 ms to transmit.
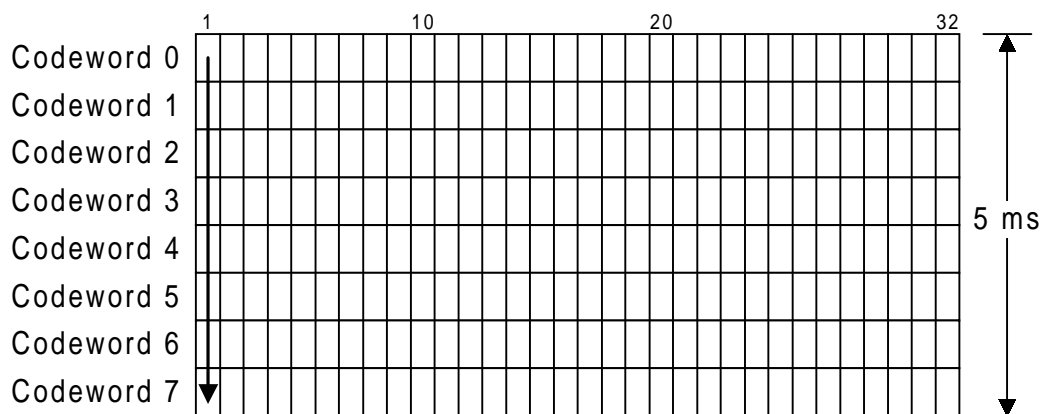
Figure 2-5 Block interleaving for 1600 bps

The transmission of the data bits still follows the modulation type and baud rate. For 2-FSK, the bit transmission is straight forward. Each bit is mapped to one of two frequencies for the period of the baud rate. For 4-FSK, two bits, each bit from the same column of an adjacent codeword, are mapped to one of four frequencies for the period of the baud rate.

2.3.3 Codeword

Each codeword in FLEX is 32 bits long and uses the same error correction technique as POCSAG. Figure 2-6 shows the format of this codeword. The data consists of a (31,21) Bose-Chaudhuri-Hocquenhem (BCH) forward error correction with an additional even parity bit to make up the 32-bit word.
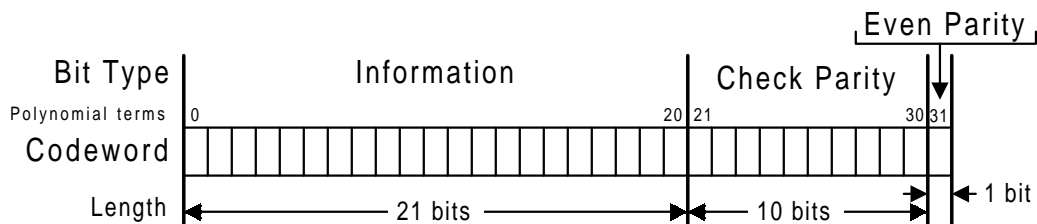
Figure 2-6 FLEX codeword

The BCH code contains 21 information bits and 10 parity which are calculated with the standard generating polynomial, g(x), for the (31,21) BCH code.

$$g(x) = x^{10} + x^9 + x^8 + x^6 + x^5 + x^3 + 1$$

The first 31 data bits of the FLEX codeword correspond to the coefficients of a polynomial that has 31 terms (x^{30} to x^0). The information bits are the first 21 terms (x^{30} to x^{10}). The parity bits are generated by dividing modulo-2 the 21 information bits by the generating polynomial. The parity bits are the remainder of this division and will complete the polynomial's last 10 terms (x^9 to x^0). The last data bit of the FLEX codeword is the even-parity bit. This bit is set or cleared so that the overall bit parity of the 32-bit codeword is even, thus the number of logic ones is an even number.

2.3.4 Coding Format

The 11 blocks with a total of 88 codewords in 1600 bps FLEX is the basis of the FLEX coding format. The higher speed FLEX rates simply multiplex two or four of the 1600 bps blocks together. Each 1600 bps block is given a phase and each phase is designated with a lowercase

letter (a, b, c, d). For 1600 bps FLEX, only phase a is transmitted. For 3200 bps FLEX, phase a and phase c are transmitted and 6400 bps FLEX transmits all four phases. Each block contains eight codewords for each phase and are multiplexed together so that the time to transmit the block is 160 ms. For 6400 bps, each block would contain 8 codewords for phase a, 8 codewords for phase b, 8 codewords for phase c, and 8 codewords for phase d.

The FLEX coding format is shown in Figure 2-7. The 11 blocks are shown with the order in which information is placed. In the first codeword of the first block is the Block Information Word which is an overhead codeword needed to identify the remaining codewords. The 2nd to 88th codewords will be the address field, vector field, message data field, and idle codewords field. The number of codewords used in each field is based on the information transmitted. The address field identifies one or more pagers. The vector field identifies each pager's message type and where the message content is located in the message field.
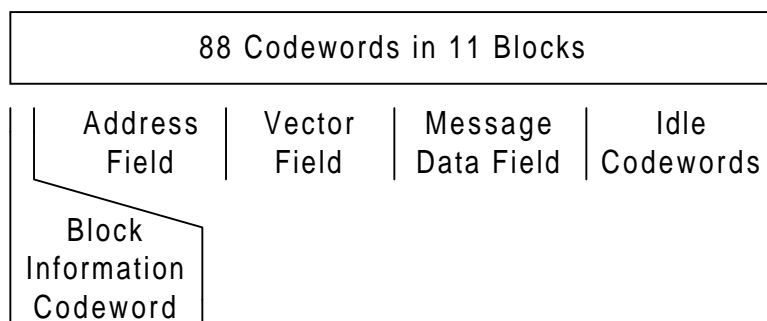
Figure 2-7 FLEX coding format

The number of codewords required for the FLEX coding format for tone, 10 digit numeric, and 40 Character Alphanumeric page compared with POCSAG are shown in Table 2-1. The number of codewords does not include the overhead codes associate with each paging standard. For each 1600 bps FLEX coding format, there is one overhead codeword per 88 codewords which is the block information codeword. For POCSAG, there is one overhead codeword per 17 codewords which is the synchronization word. The percent of the coding format designated for overhead information is reduced from 5.88% for POSCAG to 1.14% for FLEX.

Table 2-1 Codewords per paging type

Paging Standard	POCSAG	FLEX
Tone	1	2
Numeric$_{10 \text{ digit}}$	3	4
Alphanumeric$_{40 \text{ Char}}$	15	17

2.4 Fading Tolerance

The robust nature of FLEX can be seen both in the synchronization period and the interleaved data bits in each block. The protocol has been designed to tolerate fades up to 10 ms in duration in the synchronization period and in each data block. Fading is the result of a frequency that is temporarily received at a signal less than the median signal level. How much the signal is less than the median level is the depth of the fade and how long the signal is less than the median is its duration. When the frequency in the operational bandwidth of the pager fades, the received signal level compared to noise or signal to noise ratio (SNR) decreases. The smaller the SNR, the more likely the data will be detected incorrectly. Thus as SNR decreases, the bit error rate (BER) increases. Fading causes the BER to be large for a short period of time. Fading tolerance is important to paging operators because it spreads the effect of the fade over a long period of time. By spreading the effect of the fade, the overall BER can be reduced to a level that is correctable with the BCH code. Pagers operate in a mobile environment which is very susceptible to fast and slow fading. [Rap 96] shows the effect of fading in urban environments. Motorola chose the 10 ms fading tolerance so that FLEX would achieve a much better fading tolerance than POCSAG. [Mot 94] contains the Table 2-2 which shows the reduced effect of the fading environment of FLEX compared with POCSAG.

Table 2-2 Relative signal strength for 99% success rate of 80 characters alphanumeric message

Paging Standard	POCAG 512	POCSAG 1200	FLEX 1600	FLEX 6400
Gaussian reference	-125.3 dBm	-123.2 dBm	-121.7 dBm	-118.2 dBm
Fading Environment	-102.2 dBm	-95.9 dBm	-107.2 dBm	-104.2 dBm
Fading Degradation	23.1 dB	27.3 dB	14.4 dB	14.0 dB

Fading environment: Single Rayleigh fade with Doppler frequency = 6.85 Hz which is 5 mph @ 900 Mhz.

The first part of the FLEX synchronization (Sync1) is set up such that a 10 ms fade, which is 16 bits at 1600 bps, will not effect both synchronization words in the same fade. The 16 bits of dotting between the synchronization words ensures that at least one sync codeword will be decoded. Thus a 10 ms fade can be tolerated during the 115 ms synchronization for a FLEX pager to decode only one sync codeword and to continue processing the frame. The interleaving of the data bit in a FLEX block allows up to 16 consecutive bits to be in error for 1600 bps, because when the data is de-interleaved, each codeword will only contain 2 bit errors and the BCH forward error correction will correct them. For 3200 bps, 32 consecutive bits can be in error, and for 6400 bps, 64 consecutive bits can be in error. The data in a block are transmitted by column and each column takes 5 ms to transmit, so two consecutive columns form 10 ms of data. Thus a 10 ms fade can be tolerated during each of the 160 ms blocks.

2.5 FLEX and POCSAG mixed

The integration of FLEX with other asynchronous paging standards is quite simple. A FLEX system must be setup to send a minimum number of frames per cycle. For example, the paging operator wants FLEX pages to be sent every 30 seconds. The system software simply reserves 1.875 every 30 seconds for a FLEX frame. If multiple FLEX frames are required to send the information then additional frames are transmitted until all the information is sent. During the non-FLEX time other asynchronous paging data can be sent. If no FLEX paging data is available at the 30 second interval then a frame does not have to be sent. Since FLEX is a synchronous

system it does require a frame to be sent with a minimum time so that timing between the pager and transmitter is not lost.

Chapter 3

3. Receiver and Decoder Design

3.1 Receiver

The receiver which forms the front end of the FLEX decoder is a non-coherent FSK receiver. Figure 3-1 shows a block diagram of the receiver. The receiver is a dual-conversion superheterodyne design and contains two local oscillators to mix down the 929-932 MHz signal to a 455 kHz signal with a 15 kHz BW. The receiver is linear up to the test point (TP). The signal is then detected using the Philips NE605 [Phi 96] limiter to produce an FM demodulated output. The output of the limiter is a DC coupled discriminated audio signal. The DC coupled audio is important to use when detecting FSK signals that have no guaranteed transition changes per bit. AC coupling is performed with a capacitor that couples the changes in the voltage on a reference DC voltage. AC coupling is pattern sensitive and will not decode properly with a threshold comparator.
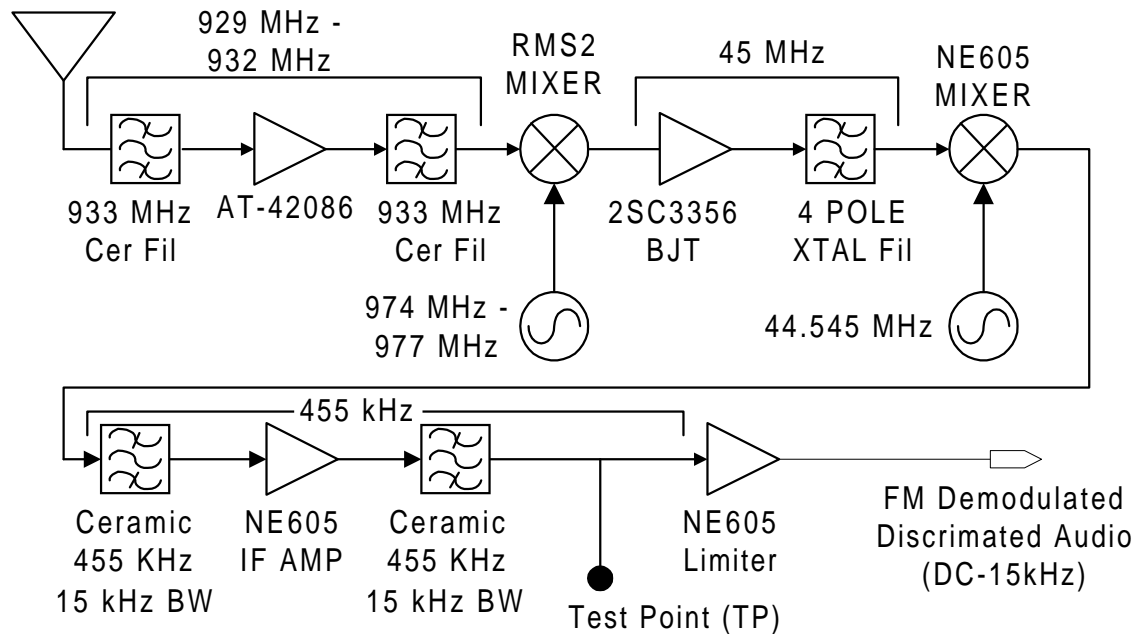
Figure 3-1 Receiver block diagram

The receiver's design of mixing the signal down has the possibility of inverting the data depending on which signal is filtered when the down conversion is performed. From the law of cosine the product of two cosine waves are

$$\cos(\omega\, t)\bullet\cos(\alpha\, t)=\frac{1}{2}\cos[(\omega-\alpha)t]+\frac{1}{2}\cos[(\omega+\alpha)t]$$

When this is converted to the frequency domain, there are two impulses: one at $\omega + \alpha$ and one at $\omega - \alpha$. There are two possible ways to mix the signal down to an intermediate frequency (IF): low side injection and high side injection. Low side injection is when the local oscillator (LO) into the mixer is less than the input frequency. High side injection is when the LO is greater than the input frequency. Since the receiver is only mixing down the frequency the $\cos[(\omega - \alpha)t]$ is the only term that is used. Figure 3-2 shows how normal FM demodulation maps a frequency to a voltage and the higher the frequency the higher the voltage. Data inversion occurs when two frequencies are such that f_{bit1} is greater than f_{bit0} but after mixing down f_{bit1} is less than f_{bit0}. Data inversion is not a problem, it just needs to be known so that the correct symbol is decoded.

For high side injection

$$f_{lo\text{-}high} > f_{bit1} > f_{bit0}.$$

when mixed down

$$f_{IF\text{-}bit1} = f_{lo\text{-}high}\text{-} f_{bit1} \qquad f_{IF\text{-}bit0} = f_{lo\text{-}high}\text{-} f_{bit0}$$

since $f_{bit1} > f_{bit0}$ then

$$f_{IF\text{-}bit1} < f_{IF\text{-}bit0}$$

Data inversion occurs with high side injection.

For low side injection

$$f_{bit1} > f_{bit0}.>f_{lo\text{-}low}$$

when mixed down

$$f_{IF\text{-}bit1} = f_{bit1} - f_{lo\text{-}low} \qquad f_{IF\text{-}bit0} = f_{bit0} - f_{lo\text{-}low}\text{-}$$

since $f_{bit1} > f_{bit0}$ then

$$f_{IF\text{-}bit1} > f_{IF\text{-}bit0}$$

No data inversion (normal FM demodulation) occurs with low side injection.

For the given receiver, the receiver uses high side injection to mix the signal down to 45 MHz so that data is inverted. Then the low side injection is used to mix the signal down to 455 KHz which does not inverted the data so the overall data is still inverted. The NE605 limiter is a quad detector that inverts the data so the overall data pattern is not inverted by the receiver. Data inversion can be handled by inserting an inverting amplifier with unity gain after the FM discriminator so that the data pattern is corrected.

The ideal frequency vs. FM discriminated voltage for a non-inverted receiver is shown in Figure 3-2. The output voltage at the tuned or center frequencies is V_{f_c}. A frequency greater than the center frequency will produce an output voltage larger than the center frequency voltage. Likewise a frequency less than the center frequency will produce an output voltage less than the center frequency voltage.
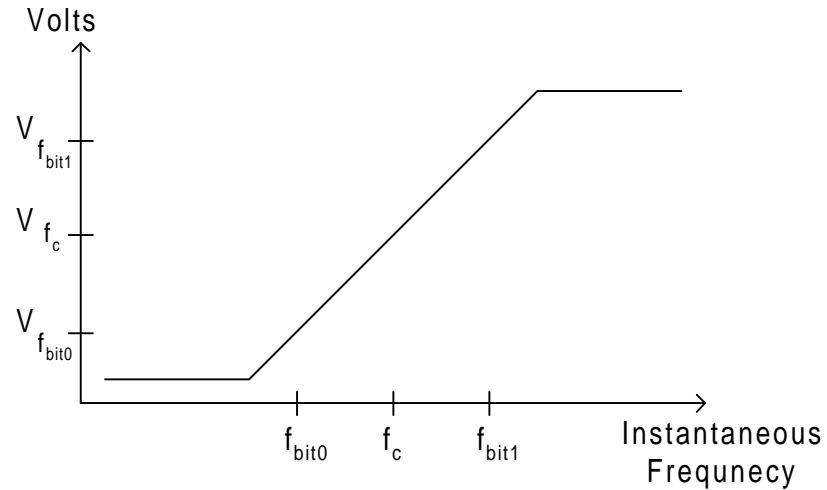
Figure 3-2 Ideal frequency vs. FM discriminated voltage

3.2 Decoder

The design goal of the decoder board was to implement a real-time FLEX decoder using a low power microprocessor based system, which is much cheaper than a high power digital signal processor (DSP) system. Figure 3-3 shows how the decoder board first converts the time varying DC discriminator audio into digital levels.
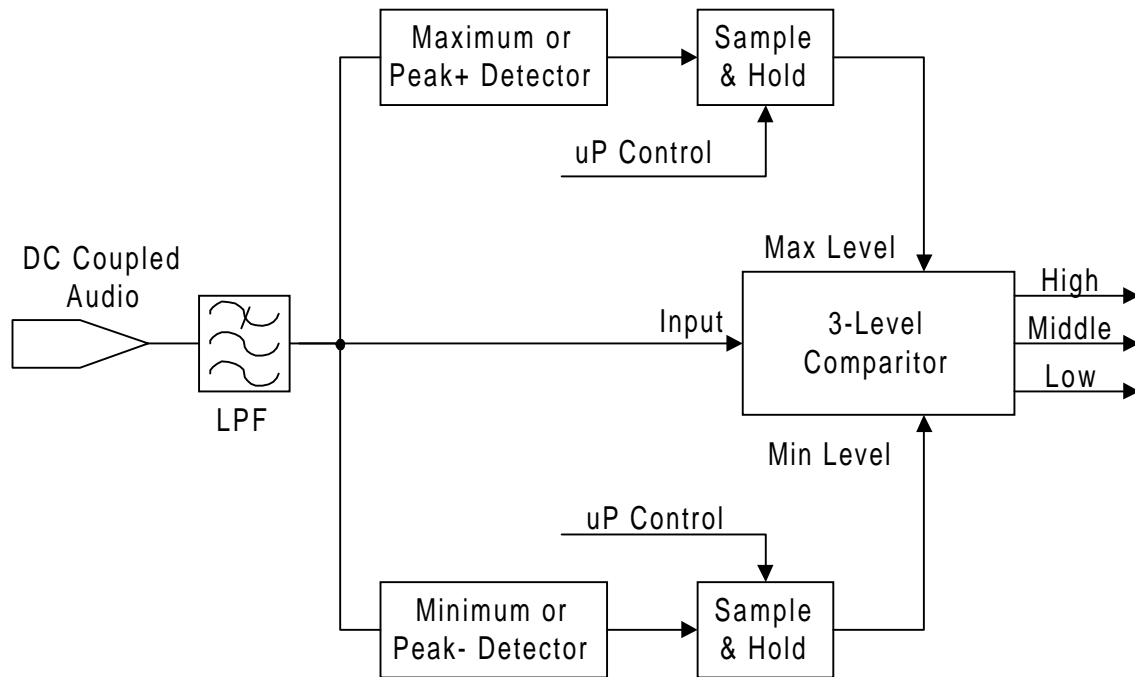
Figure 3-3 Decoder discrimination

The DC Coupled Audio signal first passes through a low pass filter (LPF) to remove any high frequency components (455 kHz) that occur due to the mixing down of the RF signal by the receiver. The LPF is also required to improve the signal to noise ratio by reducing the bandwidth so that the best ratio of signal power to noise bandwidth power is achieved. The exact cut-off frequency and the order of the filter is propriety to the FLEX protocol. The filtered audio passes to two peak detectors: Peak+ Detector and Peak- Detector. These are discrete circuits that determine the two extremes of the discriminated audio. Figure 3-4 shows both Peak Detector circuits [Gra 71] used on the decoder. For the Peak+ Detector, when the filter audio voltage (V_{in}) is greater than V2, the diode D2 allows current to pass and the OP amp, TL2272, will bring its - input (V2) equal to its + input (V_{in}). The capacitor C2 charges with the time constant:

$$t = R \bullet C = 27\Omega \bullet 3.3\mu F = 89\mu s$$

For 3200 baud data, the period is 312μs so that it will take 2 dotting bits (1 high and 1 low) to charge the capacitor of both peak detectors to be within 3 dB of the desired voltage. The term pump-charged capacitor is used to describe this procedure, because for every bit one of the peak

detected are "pumped-up" to their desired value. The Peak- Detector works in the same manner as the Peak+ Detector with the exception that D1 allows current to flow when V_{in} is less than V1. In the FLEX protocol there are 32 dotting bits, which is enough time to bring Peak+ and Peak- to their desired values.
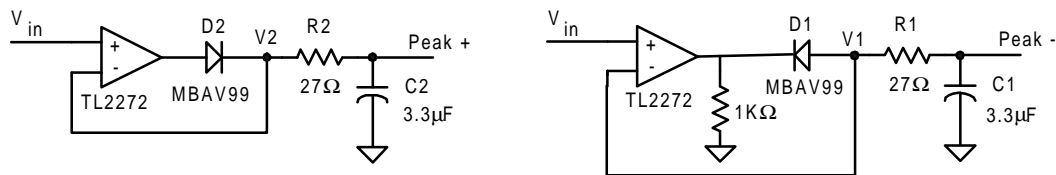
Figure 3-4 Peak + and Peak - Circuits

The detected extremes are then passed through a sample and hold. The microprocessor will determine when to hold the extremes. A problem with using pump-charged capacitors is the decay time after it is "pumped" (reached its maximum voltage). Thus the maximum voltage needs to be received by the pump charged capacitor circuit within the decay time. In the FLEX paging protocol the synchronization period is the only guaranteed time when the two extremes will occur for a significant length of time. The extreme values will be held constant after synchronization by the microprocessor (uP) using a sample and hold chip (Analog Devices SMP-04). The decay time of the sample and hold chip is on the order of seconds so the 1.875 ms between frames is enough to guarantee that the extreme level held valid with the sample and hold chip. Every new frame will cause the sample and hold chip to re-sample a new extreme value during the Sync1 period of the protocol. The extreme values are then used to by the 3 Level Comparator to output limited data (TTL levels) for sampling.

With the extreme level determined, the symbols can be determined using threshold comparators. Figure 3-5 shows the frequency and symbols relationship with 4-FSK FLEX data. The receiver's FM discriminator converts frequency to a voltage in a linear manner. The voltage at the maximum extreme is V_{Max} and the minimum extreme is V_{Min}. These voltage are determined

using the pump-charge capacitors and held by the sample and hold chip after Sync1 is detected. During Sync1, the voltage from the pump-charged capacitors are used directly, because the peak voltages are being received. A three comparator system is used to determine the two bit symbol. The same comparators work for 2-FSK data but only the center or average threshold is needed. The threshold voltage level for each is shown by the wider dotted line in Figure 3-5.

```
Frequency      Voltage
Deviation      Levels        Bit Pattern

+4.8 kHz  ····· V_Max  ············
+3.2 kHz   —   V_T-High — — —
+1.6 kHz  ·······················
   0 kHz   —   V_T-Avg — —
-1.6 kHz  ·······················
-3.2 kHz   —   V_T-Low — —
-4.8 kHz  ····· V_Min  ····

                    00 11 10 01
                    Symbol Values
```
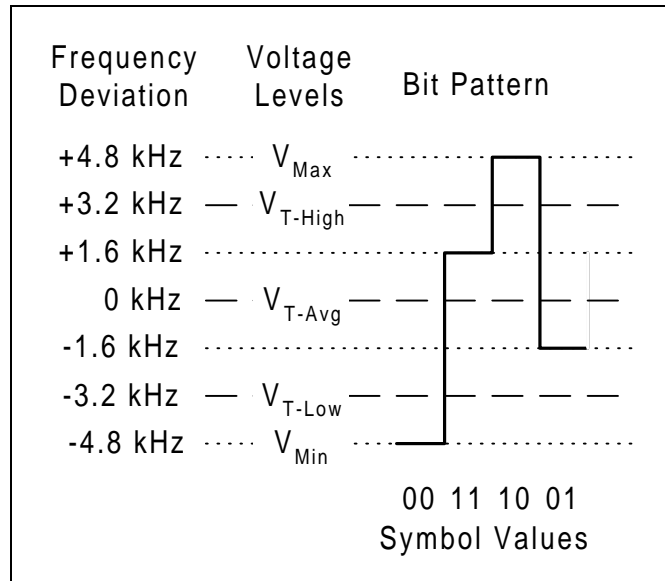
Figure 3-5 Frequency deviation, threshold voltage level, and 4-FSK symbol relationship

Since the difference between two adjacent levels is 3.2 kHz, the threshold voltage is set to half way between two adjacent levels. The first comparator that needs to be examined is the center comparator whose threshold voltage is

$$V_{T-Avg} = \frac{V_{Max} + V_{Min}}{2}$$

where V_{T-Avg} is the average or center comparator voltage level.

Only one of the other two comparators needs to be examined after the value of the center comparator is known. The threshold voltage for the high side comparator (used when center comparator outputs a logic 1) is

$$V_{T-High} = \frac{2\left(V_{Max} - V_{T-Avg}\right)}{3} + V_{T-Avg}$$

which reduces down to

$$V_{T-High} = \frac{5V_{Max} + V_{Min}}{6}$$

The threshold voltage for the low side comparator (used when center comparator outputs a logic 0) is

$$V_{T-Low} = \frac{V_{T-Avg} - V_{Min}}{3} + V_{Min}$$

which reduces down to

$$V_{T-Low} = \frac{5V_{Min} + V_{Max}}{6}$$

The comparator threshold levels are dependent on the values of V_{Min} and V_{Max}. Figure 3-6 shows how these levels were determined using a resistor divider. For V_{T-Avg}, the values of the resistors must be

$$R1 + R2 = R3 + R4$$

so that the voltage drop from V_{T-Max} to V_{T-Avg} and V_{T-Avg} to V_{T-Min} are the same. For both V_{T-Min} and V_{T-Max} the voltage drop ratio from R1 to R2 and R4 to R3 must 1/3. Using the resistor divider rule,

$$\frac{R1}{R1 + R2} = \frac{1}{3}$$

which reduces to

$$R2 = 2 \bullet R1$$

Similarly for R3 and R4,

$$R3 = 2 \bullet R4$$

The author chose a value of R1 which would be much greater than the 27Ω resister in the pump-charge so that its resistance can be ignored. Thus a value of 2.49 KΩ was chosen for R1 which is about 100 times 27Ω. This led R2 to be determined as 4.87 KΩ(closest resistor to 4.98 KΩ). The symmetry around VT-Avg meant that R4=R1 and R3=R2.
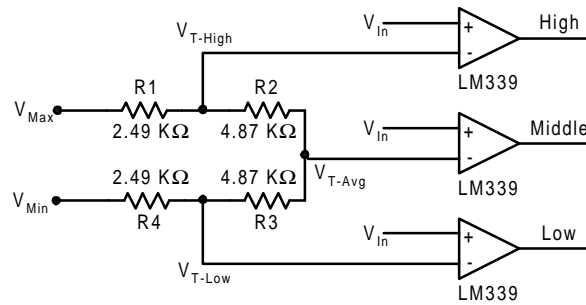
Figure 3-6 Resistor divider used to detect threshold voltage levels

Figure 3-6 also shows how these levels are used at negative inputs into a comparator (LM339). If the input voltage (V_{in}) is less than the threshold then the output of the LM339 is a TTL low, otherwise the output is TTL high.   The limited data (High, Middle, and Low) is then simultaneous clocked into three shift registers. The sampled data can then be directly read by the microprocessor. Figure 3-7 shows a block diagram of how this occurs. The microprocessor can control the sample rate. The approach taken with this design was to sample at 8 times the baud rate. Thus the sample clock will be running at 12800 Hz for 1600 baud or 25600 Hz for 3200 baud.
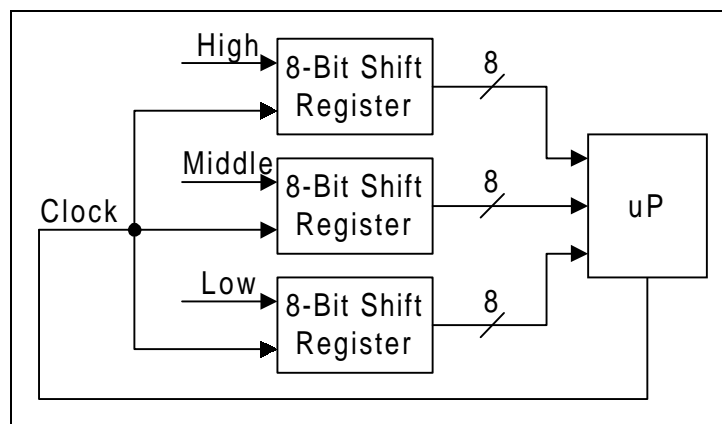
Figure 3-7 Limited Data into Microprocessor

The microprocessor must perform symbol determination and symbol clock synchronization in order to accurately recover the data.

The symbol determination was performed by first determining the most significant bit (MSB). Bit determination is the majority bit in the shift register or metric of data. This was implemented with a look up table for speed. Because of timing jitter, which is corrected for by the synchronization, and symbol transition time, not all 8 samples are used to determine the bit. For the MSB, the middle 6 samples were used to determine the bit and only the middle 4 samples were used to determine the least significant bit (LSB). The MSB is determined from the middle sample shift register. Once the MSB is determined, the LSB is determined from the either the low sample shift register or high sample shift register based on the MSB. If the MSB is a logic 1, then LSB is determined from the high sample shift register. The Gray coding requires that result of this LSB be inverted so that symbol associated with the highest deviation be 10. If the MSB is a logic 0, then LSB is determined from the low sample shift register. The Gray coding requirement is correct with this LSB since the symbol associated with the lowest deviation will be 00.

Symbol determination is using the sampled data to determine one of the four possible symbols for 4-FSK or one of two possible symbols for 2-FSK. The ideal symbol determination would be to integrate over the entire symbol and the result would map into one of the possible symbols. This approach is very similar but a few variations. First the data from the discriminator are limited to a logic 1 or 0 thus there is no resolution of how close each sample is to the threshold voltage. Also the data is only sampled 8 times in a symbol period. An ideal integrator would have an infinite number of samples. Also all 8 samples might not be in the same symbol period due to clock variations. Adjustment of the sample clock is performed with the symbol clock synchronization algorithm.

The symbol timing is determined with each MSB. The 8 samples in the middle shift register are examine to see where the bit energy is centered. If the bit energy is centered around the middle, which is bits 3 or 4, then the next sample will be taken in 8 clocks. If the bit energy is centered toward the more recent samples, which is bits 0, 1, or 2, the next sample will be taken in 9 clocks. This is a lag condition in which the sample clock is delayed so that the next bit will be

centered. If the bit energy is centered toward the older samples which is bits 5, 6 or 7, the next sample is taken in 7 clocks. This is lead condition in which the sample clock is increased so that the next bit will be centered. Just as the bit determination is implemented with a look up table for speed, so is the symbol timing.

The sample clock used in this design is divided down by a crystal that is rated at ± 100 ppm so this means the sample clock can be off by ± 0.01 %. For the data to slip 1/8 of a symbol time it would take 1/8 divided by 0.01% or 1250 bits minimum before a symbol timing needs to be adjusted.

3.3 Microprocessor software implementation

The microprocessor used in this design was a Dallas 80C320 which is a fast 80C31/80C32-compatiable microcontroller [Dal 93]. The DS80C320 uses the 8051 instruction set with an average speed improvement of 2.5 time faster. The microprocessor software was implemented using some of the inherent features of microprocessor. The microprocessor had two processes running at the same time: interrupt processing and main processing. The interrupt processing was used for the time critical process of symbol determination and collection and maintaining symbol timing. The main processing was used to examine the collected data for the FLEX protocol and report the formatted data.

The previous section described how the microprocessor determined the symbol and maintained clock synchronization. This is what is occurring during the interrupt processing. Figure 3-8 is the block diagram for the interrupt processing. The processes Determine Bit and Determine Next Symbol Time in Figure 3-8 are implemented using a table look-up of the 8-bit sampled value. This allows fast determination of bit and next timing value. The symbol timing is loaded into a counter that decrements with each sample clock. When the count goes to zero, the interrupt occurs. The main processing loop is temporarily suspended while the interrupt is processed. Figure 3-8 is only provided to illustrate how the software process is implemented. For a

complete description of how the decoder determines each symbol and maintains symbol clock timing, the reader is referred to Section 3.2 and Figure 3-7 in that section.
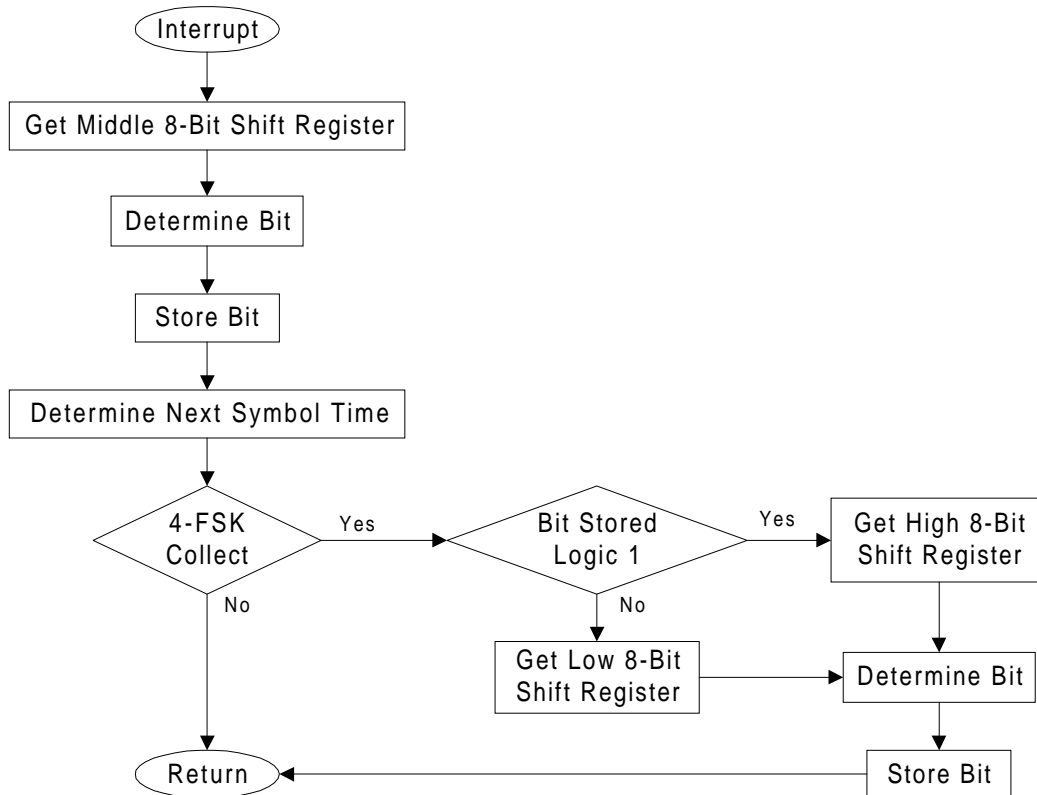
Figure 3-8 Interrupt processing block diagram

At the beginning of a FLEX transmission, the decoder can begin sampling any where in the symbol period so the decoder needs to move its sampling point to the start of a symbol. The dotting sequence in the beginning of FLEX synchronization enables the symbol clock synchronization to move the sampling point to the beginning of a symbol. Figure 3-9 illustrates the software flow diagram of the main process to decoder a FLEX frame. The software processes that begin with "Interrupt:" are processes that change the way the interrupt process collects data. The interrupts collect data at 1600 baud or 3200 baud and as 2-FSK data or 4-FSK data.
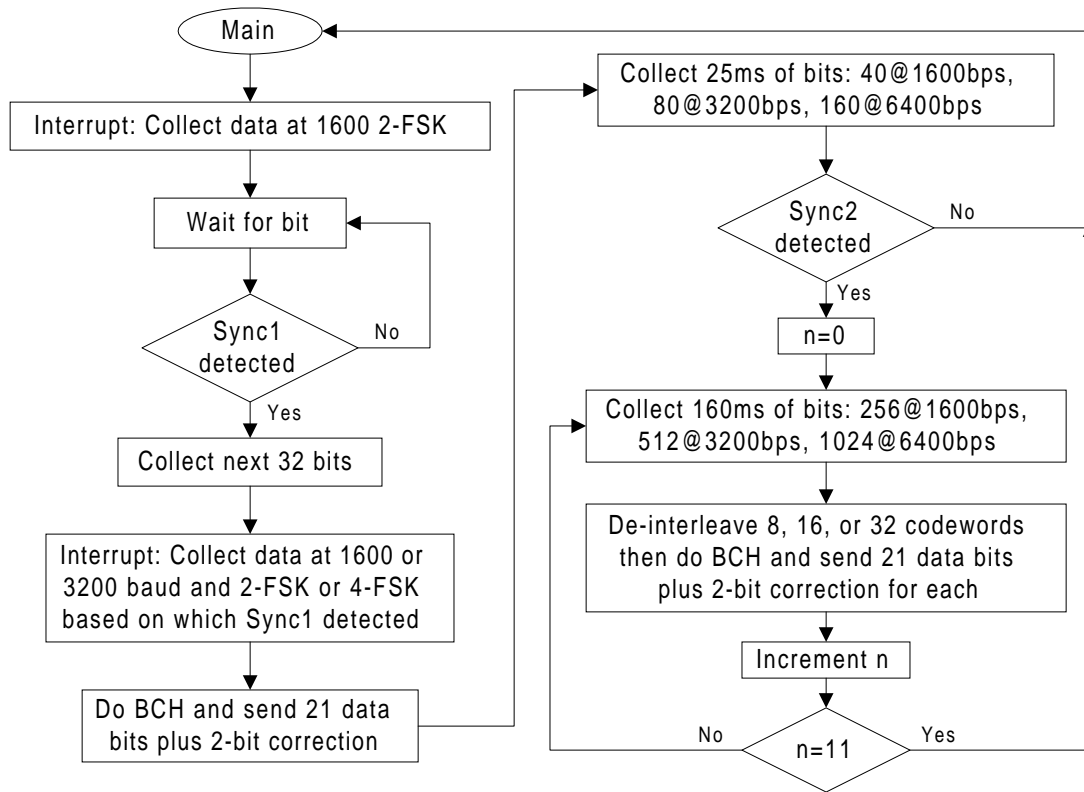
Figure 3-9 Main processing block diagram

The main process directs the interrupt to start collecting data at 1600 baud and 2FSK. With every new bit received in the interrupt, the main process examines the collected data for one of the four Sync1. Section 2.3.1 describes FLEX frame format and the software actually reports via the serial port (not shown in block diagram) which Sync1 was receive and a 2-bit error factor. The 2-bit error factor is the number of bits required for the receive codeword to expected codeword. The 2-bit factor is converted to decimal to get the number of bit errors. Thus only 3 bits are allowed to be in error for the codeword to match. When the complete Sync1 is detected, the frame information word is then collected. After the frame information is collected the interrupt process is directed to the new baud and bits/symbol rate based on the Sync1 received. The BCH forward error correction algorithm is then applied to the 32 bits collected for the frame info. The BCH forward error correction algorithm will be described in detail later in this section. Suffice it to say that this algorithm attempts to correct the 32 bits to a valid 32-bit codeword and

returns a 2-bit error correction factor. The software then sends the 21 data bits (see Section 2.3.3 for codeword structure) and the 2-bit error correction factor via the serial port. The 2-bit error correction factor is similar to the one described in the reporting of the Sync1 detected.

All data that is now collected is with new baud rate of 1600 or 3200 and the bits/symbol is either 1 (2-FSK) or 2 (4-FSK). Sync2 is collected first and compared to the expected Sync2. If Sync2 is not within 3 bits of expected then the software reports an error with Sync2, otherwise a good Sync2 is reported with a 2-bit error factor (not shown in block diagram). The 11 blocks of interleave are now collected. The block number is shown as "n" in the block diagram. The 160 ms of data are collected. The data is de-interleaved by simply reversing the interleave process described in section 2.3.2. The number of codewords that will be de-interleaved is 8, 16, or 32 based on the respective data rate 1600, 3200, or 6400 bps. For each codeword, the BCH forward error correction algorithm is employed on the codeword. The software then sends the 21 data bits, the block number, word number interleaved, and the 2-bit error correction factor via the serial port.

The standard BCH decode algorithm as defined in [Lin 83] involves three steps. Compute the syndrome, S, from the received data, determine the error-location polynomial, $\sigma(z)$, from the syndromes, and then determine the error-location numbers by finding the roots of the error-location polynomial. There are two syndromes that need to be calculated with the (31,21) BCH: S1 and S3. Both are calculated by dividing the received pattern by the minimum polynomials M1 and M3.

$$M1 = X^5 + X^2 + 1$$
$$M3 = X^5 + X^4 + X^3 + X^2 + 1$$

The routine used to calculate this division is quite simple in an 8-bit micro-processor. It requires two working division registers: m1 and m3. Each received bit is shifted into the LSB of the working m1 register. If the bit in the 5th bit location of m1 is a logic one then m1 is exclusive ORed (XORed) with the value 0x25, otherwise m1 is not changed. The same process is performed with the working m3 but the value XORed is 0x3D. This accomplishes in software

what would be implemented in hardware with taps at each location. After all 31 bits pass through these two shifting registers, the resulting m1 and m3 are used to calculate S1 and S3. Syndrome 1 is simply the result in m1 (S1=m1). The calculation for Syndrome 3 which uses m3 is given below. The notation of S3.0 means Syndrome 3 bit location 0. All addition with m3 bit location is modulo 2.

S3.0 = m3.0

S3.1 = m3.2+ m3.3+ m3.4

S3.2 = m3.4

S3.3 = m3.1+ m3.2+ m3.3+ m3.4

S3.4 = m3.3

The error-location polynomial, $\sigma(z)$ will be one of the following based on S1 and S3 [Mac 77].

i)   If S1=S3=0, $\sigma(z) = 0$. (No errors)

ii) If S1 != 0, S3 = $S1^3$, $\sigma(z) = 1+S1z$. (1 bit error)

iii) If S1 != 0, S3 != $S1^3$, $\sigma(z) = 1 + S1z + ((S3/S1 + S1^2)z^2$. (2 bit errors)

A table look up of the Galois Field (GF) for the minimum polynomial m1(x) is given in [Lin 83]. An inverse table to the GF is also used so that multiplication of values can be done using the GF index or power so that addition can be used. The error-location polynomial is evaluated for each bit $\sigma(\alpha^i)$ and if the result is zero then that bit is in error. The overall even parity bit was also used to help determine the number of bits in error. An incorrect received even parity means that there are an odd number of bits in error, and a correct received even parity means there is an even number of bits in error. The parity bit itself might be a bit in error and it is not included in the BCH error encoding.

3.4 BER Measurements

The number of bits required for a valid BER measurement is determined by the method "bounded binomial sampling" which is used as one of the method in [Fun 91]. Bounded

binomial sampling provides a boundary on how many bits must be collected for an accurate BER measurement. Accuracy is given in terms of certain relative precision and a certain absolute precision. [Cro 76] describes this method and give figures for the minimum number of bit errors required for relative precision and minimum number of bits for an absolute precision. The test procedure did not allow for an exact adherence to the stop condition as described in [Cro 76] and used by [Fun 91]. Instead the test time was the major factor, so the total number of bits measured was based on this restriction. The research was more interested in the performance at high BER than at low BER. Absolute precision is the deciding factor with high BER measurements. The goal was to measure a minimum number of bits so as to have a relative precision of 1 bit in a FLEX 6400 bps frame. Since there are 352 codewords in a 6400 bps frame the BER would be 8.9e-5. From Figure 2 in [Cro 76] that requires 3e+8 bits to measure. Test time prevented this from being achieved. Instead 1.7e+8 bits were measured. Given this as the minimum number of bits the absolute precision would be about 1.2e-4 which is 1.4 bits in a 6400 bps frame.

A known randomly generated pattern, FLEX encoded, will be transmitted at a known power level. This power level will be decreased so that an E_b/N_o plot can be generated for uniform comparison. The energy per bit, E_b, is the signal power divide by number of bits per second. Only 6400 bps FLEX is being measured, so E_b is received power divided by 6400. The noise spectral density, N_o, is the noise power divided by equivalent noise bandwidth. Chapter 4 gives a more detailed description of the noise power and equivalent noise bandwidth. If the received codeword is correct (compared to the known randomly generated one) then the 2-bit error correction bits will be used to determine the number of bits in error, and the total usable bits is incremented by 32. If the codeword is not corrected then it is counted as a codeword erasure. In either case a total codeword count is incremented. If the frame is missed then it is a frame erasure. There are two frame erasures, one due to sync1 not being detected (An) and another due to sync2 not being detected (Comma). In either case of a frame received or missed the total frame count is incremented. The following are how the BER is calculated taking into account the various erasures.

BER bits = bits in error / total usable bits

BER CW = codeword erasures / total codewords

BER Frame = (An erasures + Comma erasures) / total frames

Block BER =(bits in error + (32 * codeword erasures)) / (total codewords * 32)

System BER = (bits in error + (32 * codeword erasures) + ((An erasures + Comma erasures)* 11264)) / (total frames * 11264)

The following is how E_b/N_o is computed

E_b/N_o (dB) = 10*Log(((Tx Power - cable loss)(mW)/6400) / N_o(mW))

The BER versus E_b/N_o results for each receiver that will be compared are BER bits, BER system, and BER 4FSK. BER bits and BER system are measured and BER 4FSK is the ideal BER for 4-level FSK non-coherent detection taken from [Lat 89].

Chapter 4

4. Measurements

All measurements were performed on three receiver/decoder pairs. The Grayson serial number for the three receivers were AS4928, AS4927, and AS2387. All measurements were performed with the receiver tuned to 930 MHz which is near the center of the paging spectrum. Thus all signal generators were tuned to 930 MHz for these measurements. Due to time limitations, only two of the three receivers measured have BER measurements and plots.

4.1 Linear Receiver

Figure 4-1 illustrates the measurement setup for confirming that the receiver is linear up to TP for small signals. The HP8657A signal generator had its output power stepped from -125 dBm up to -80 dBm in 5 dB steps. At each level, the peak power measured by the spectrum analyzer is recorded. The actual dBm measurement taken at each RF level is not important, just the difference between levels.
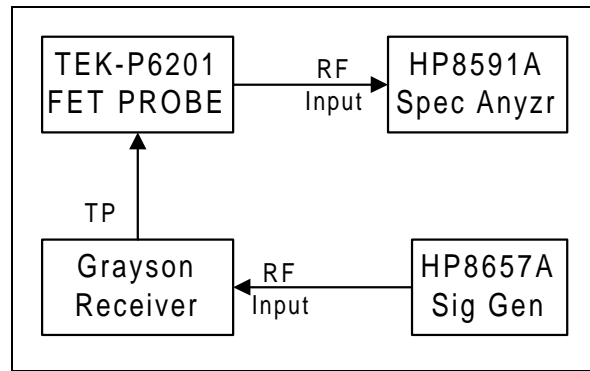
Figure 4-1 Linearity measurement

The HP8591A spectrum analyzer was setup with the values shown in Table 4-1. The test point (TP in Figure 3-1) is where the received signal has been mixed down to 455 KHz. The filter bandwidth was 15 KHz so the span was set to 50 KHz to ensure the entire signal is received. The resolution bandwidth of 1 KHz was chosen as an adequate bandwidth so that the signal can be displayed but not too fine that the sweep time would not be very long. The video averaging was enabled so that variations in signal power due to noise at small input signal levels (-125 dBm) would be averaged out. 50 samples required only 15 seconds to acquire. The Tektronics P6201 FET probe is a 50Ω impedance probe that can be used over a wide frequency range that includes 455KHz. Measuring only differences does not require the probe to be match.

Table 4-1 HP8591A spectrum analyzer setup

Setting	Value
Center Frequency	455 KHz
Span Frequency	50 KHz
Resolution Bandwidth	1KHz
Sweep Time	Auto (300 msec)
Video Average	On with 50 Averages
Video BW/Resolution BW	1.0
Y Display	Log (dB)
X Display	Linear (Hz)

4.2 Equivalent noise bandwidth

The equivalent noise bandwidth of a receiver is defined as the width of a fictitious rectangular spectrum such that the power in that rectangular band is equal to the actual spectrum over positive frequencies [Cou 90]. The height of the fictitious rectangular spectrum is the maximum value in the actual spectrum [Bli 76]. Figure 4-2 illustrates the measurement for making the actual spectrum of the receiver. The receiver is connected to a 50Ω load and the spectrum analyzer sweeps the actual noise spectrum over the negative (less than 455 KHz) and positive frequencies. The HP8591A spectrum analyzer had the same setup as shown in Table 4-1. The HP-IB interface of the HP8591A to a PC allows the actual video spectrum to be saved in a text format so that a computer program can be used to determine the equivalent noise bandwidth (see Appendix for program listing). The software used to interface with HP8591A was HP VEE which is a Microsoft Windows based program that allows quick control and access to various instruments. The details of HP VEE software will not be discussed because any program written to interface with HP-IB could have been used to obtain the spectrum data, and the fact that HP VEE is a very user friendly software package [Hp 93].
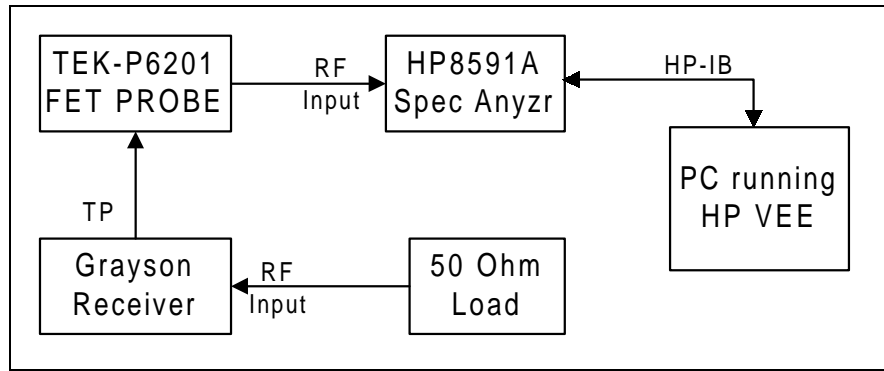
Figure 4-2 Equivalent noise bandwidth measurement

4.3 Noise power

The noise power is measured using some basic principles of signal powers and linear receivers. If two signals are independent, the combined power of each signal is simply the sum in dB of those two independent signals. For linear receivers, the sum of two equal signal powers will be 3 dB less than the power of one signal. Figure 4-1, which is the linearity measurement setup, is also the same measurement setup for measuring noise power. The HP8591A has the same setup as shown in Table 4-1 except that the resolution bandwidth is set to 30KHz. The increased bandwidth allows for smoother measurements that include the entire bandwidth (15 KHz bandpass filters). The power at the test point (TP in Figure 3-1) is measured with the RF out of the signal generator off (50Ω load) connected to the RF input of the receiver. The RF out of signal generator is enabled at -130 dBm. The signal level is increased until the power at TP is 3 dB greater than what the level was when the signal generator was off. This was easily done by using the delta marker function in the HP8591A. From mathematics, the doubling of a number is 3dB (actual $10*\log(2) = 3.0103$ dB). From [Col 85], the sum of two independent signal powers is simply the sum in dB of each power. The signal generator power and the noise power are independent signals. By increasing the signal generator so that the measured power at TP is 3 dB greater, the two signals are then at equal power. The noise power is the RF input power into the receiver which is the signal generator level minus the cable loss.

4.4 Cable loss

The cable loss measurement is shown in Figure 4-3. The HP8657 signal generator was set at level of +15 dBm. The HP8920A was set to duplex test. The tune frequency was set to automatic. With the desired cable not connected but the HP8657 and HP8920A connected, the reference level of the TX power on the HP8920A is set to zero. TX power on the HP8920A is the measurement of the received power. The desired cable is inserted and the cable loss is the TX power. The HP8920A is very accurate at measuring levels around +15 dBm. The cable loss measurement was performed on the cable from the HP8656A in the noise power measurement and in the cables and splitter in the FLEX data measurement (next section) from the HP8648A to each receiver.
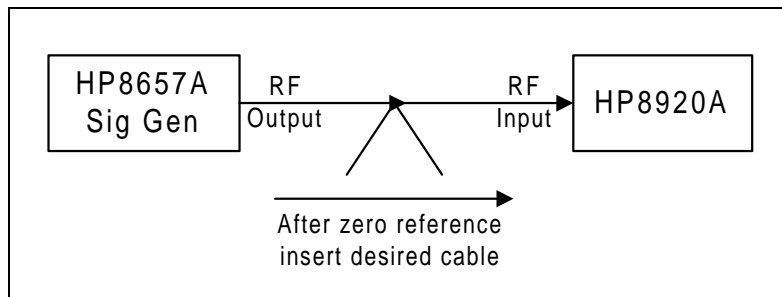
Figure 4-3 Cable loss measurement

4.5 FLEX data

The FLEX data measurement is shown in Figure 4-4. The HP8648A signal generator includes a FLEX encoder option. This option allows the frame info codeword and all block codewords to be download as arbitrary codewords for up to 128 frames or 1 cycle. The author wrote a PC program that would randomly generate the codewords for all 128 frames and download them to the HP8648A over a HP-IB interface. The Frame Info was kept unique so that the frame number

could be extracted out. The program saved the random data to a file for later processing (file number and flex rate given). The program would also adjust the output power level of the generator and start the flex encoder. The program would also stop the encoding. The listing of this program is in the Appendix. Each function that the program performed was based on its command line arguments.
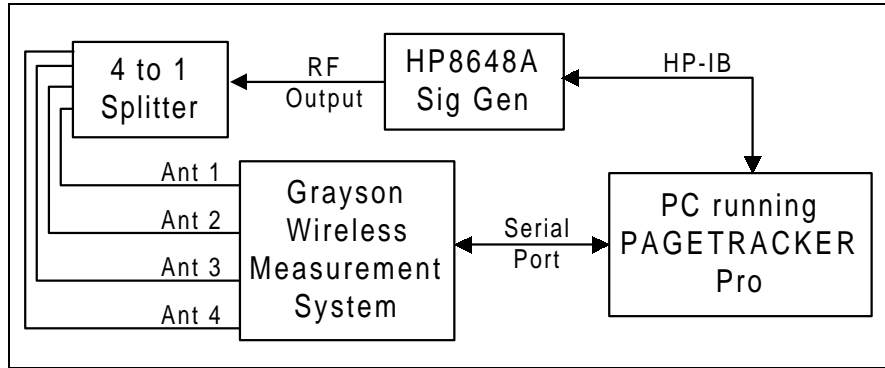
Figure 4-4 FLEX data measurement

The PAGETRACKER® Pro software, owned by Grayson Wireless, was mostly coded by the author. The code was modified to incorporate a raw FLEX data frame collected using the HP-IB program that interfaces to the HP8648A. Figure 4-5 shows the block diagram of how the test was performed. All HP8648A accesses were performed by calling the previously discussed HP-IB program with the appropriate arguments. The filename that the random data is saved to is *FLX4nnnn.RND*, where nnnn is the unique file number assigned to each random FLEX cycle. The file format for this file is shown in Table 4-2. The unsigned long int is the actual 32-bit codeword downloaded to the HP8648A.

Table 4-2 Format of *FLX4nnnn.RND* files

C variable type	name	byte size
unsigned long int	frameInfo	4
unsigned long int	blockData[352]	1408
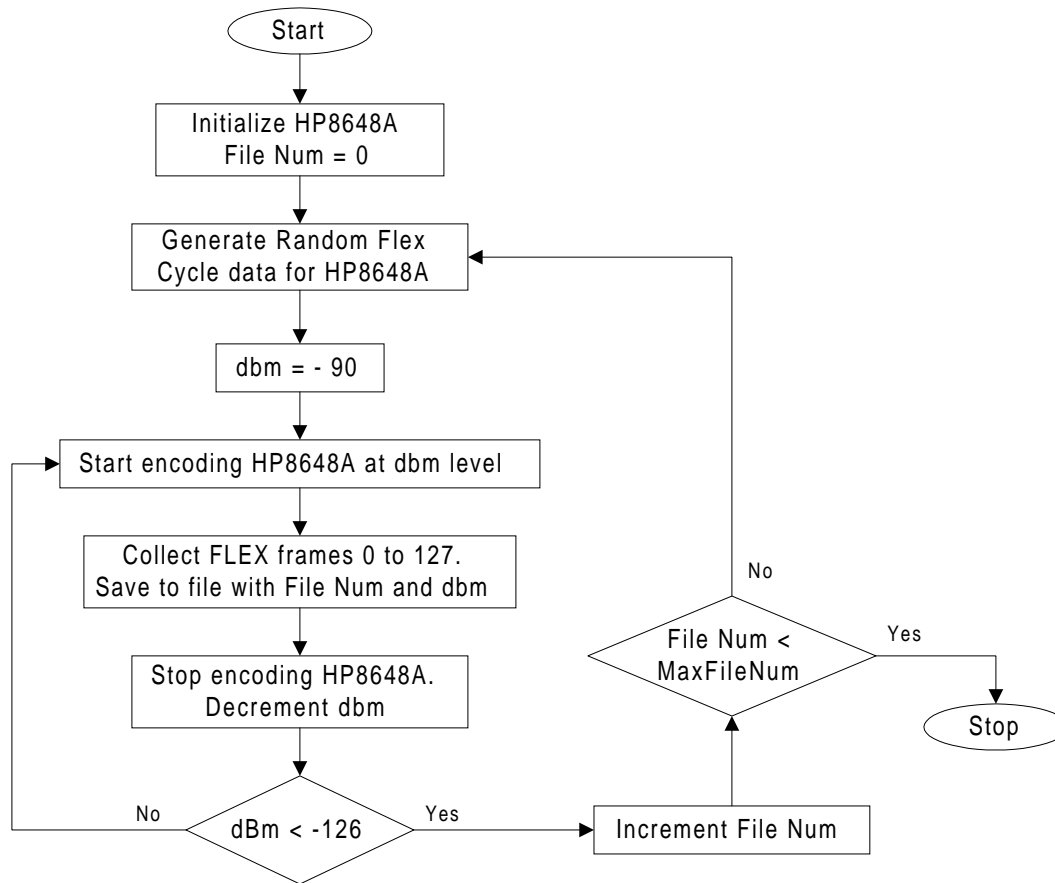
Figure 4-5 FLEX data measurement block diagram

For each frame decoded, the software sends four types of information in the following order: Sync1 detected with error bit indication, Frame info codeword, Sync2 detected with error bit indication, and 88, 178, or 352 codewords. For this test only 6400 4-FSK FLEX data was tested so there are 352 codewords. All codewords from the decoder include only the 21 data bits and a two bit error indication. The codeword and error bits were packed together in a 32-bit value (long integer) such that the 21 data bits were in bits 20 through 0 and the error bits were in bits 22 and 21. The filename that received FLEX data is *RrF4nnnn.aaa* where r is the receiver number, nnnn is the unique random sequence download to HP8648A, and aaa is the amplitude without the negative sign used by HP8648A when FLEX cycle was sent. Table 4-3 shows the file format for each FLEX frame. The file will contain up to 128 frames. Frames can be missed

due to not decoding Sync1 and thus not receiving Sync1. The *rate* is always 4 for 6400-4FSK. The *An_Errs* is the error bits for both synchronization words in Sync1. The *frameInfo* is the received 21-data bits in the frame information codeword plus the 2-bit error indication. The *C_Errs* is the error bits for both synchronization words in Sync2. The *blockData* is the received 21-data bits in each block codeword plus the 2-bit error indication. The *result* is a byte value to indicate which data was received.

Table 4-3 Format of each frame in RrF4nnnn.aaa files

C variable type	name	byte size
unsigned char	rate	1
unsigned char	An_Errs[2]	2
unsigned long int	frameInfo	4
unsigned char	C_Errs[2]	2
unsigned long int	blockData[352]	1408
unsigned char	result	1

An analyzing program was written to compare the known random pattern and each decoded pattern at each signal level to produce a resultant file of bit error rates. The source code for the analyzer code is in the Appendix.

5. Results

5.1 Linear measurement

Table 5-1 Linear measurement

level (dBm)	AS4927 (dBm)	AS4928 (dBm)	AS2387 (dBm)
-125	-54.50	-53.51	-49.75
-120	-48.94	-48.52	-44.95
-115	-43.84	-43.47	-40.27
-110	-38.40	-38.05	-34.78
-105	-33.46	-33.16	-29.75
-100	-28.39	-28.07	-24.70
-95	-23.50	-23.19	-19.91
-90	-18.53	-18.20	-15.10
-85	-15.12	-14.32	-11.63
-80	-12.04	-11.45	-9.45

The table shows that all three receivers are linear between -90 dBm and -125 dBm input power. A 5 dB change at the input results in a 5 dB change at the measured test point. Thus the receiver is measured and shown to be linear over the tested range.

5.2 Cable loss measurement

Single cable used in noise power measurements is -1.15 dB.

Table 5-2 Cable loss measurement of 1 to 4 splitter and cables

Receiver 1 AS4927	Receiver 2 AS4928	Receiver 3 AS2387	Receiver 4 Not Used
-7.61 dB	-7.52 dB	-6.73 dB	-7.44 dB

5.3 Noise measurements

Table 5-3 Noise measurement

Receiver	Noise Power	Noise Power	Noise BW	N_o(mW/Hz)
AS4927	-129.35 dBm	1.16e-13 mW	10279 Hz	1.13e-17
AS4928	-129.25 dBm	1.19e-13 mW	10085 Hz	1.18e-17
AS2387	-129.55 dBm	1.11e-13 mW	10801 Hz	1.03e-17

The noise power measurement has the effect of the cable loss factored out. The actual spectrum graph printouts are available for equivalent noise bandwidth, but the author felt that the calculations are more important. N_o is Noise Spectral Density.

5.4 FLEX Data Measurements

Table 5-4 AS4927 FLEX measurement

Tx Power	Usable bits		Codewords (CW)		Frame Erasures			BER bits	BER CWs	BER frame	BER block	BER system
	Tot. Bits	Errored	Total CWs	Erasures	Total	An	Comma					
-100	1.74e+8	0.00e+0	5.45e+6	0.00e+0	15488	0	0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0
-101	1.74e+8	1.00e+0	5.45e+6	0.00e+0	15488	0	0	5.73e-9	0.00e+0	0.00e+0	5.73e-9	5.73e-9
-102	1.74e+8	1.00e+0	5.45e+6	0.00e+0	15488	0	0	5.73e-9	0.00e+0	0.00e+0	5.73e-9	5.73e-9
-103	1.74e+8	6.00e+0	5.45e+6	0.00e+0	15488	0	0	3.44e-8	0.00e+0	0.00e+0	3.44e-8	3.44e-8
-104	1.74e+8	4.00e+0	5.45e+6	0.00e+0	15488	0	0	2.29e-8	0.00e+0	0.00e+0	2.29e-8	2.29e-8
-105	1.74e+8	1.00e+1	5.45e+6	0.00e+0	15488	0	0	5.73e-8	0.00e+0	0.00e+0	5.73e-8	5.73e-8
-106	1.74e+8	6.90e+1	5.45e+6	0.00e+0	15488	0	0	3.96e-7	0.00e+0	0.00e+0	3.96e-7	3.96e-7
-107	1.74e+8	4.66e+2	5.45e+6	4.53e+2	15488	0	0	2.67e-6	8.31e-5	0.00e+0	8.58e-5	8.58e-5
-108	1.74e+8	3.15e+3	5.45e+6	2.20e+3	15488	0	0	1.81e-5	4.04e-4	0.00e+0	4.22e-4	4.22e-4
-109	1.74e+8	2.06e+4	5.45e+6	1.08e+4	15488	0	0	1.18e-4	1.98e-3	0.00e+0	2.09e-3	2.09e-3
-110	1.73e+8	1.03e+5	5.45e+6	4.06e+4	15488	0	0	5.97e-4	7.46e-3	0.00e+0	8.05e-3	8.05e-3
-111	1.69e+8	3.85e+5	5.45e+6	1.63e+5	15488	1	4	2.27e-3	2.98e-2	3.23e-4	3.21e-2	3.24e-2
-112	1.54e+8	1.04e+6	5.44e+6	6.22e+5	15488	2	24	6.77e-3	1.14e-1	1.68e-3	1.20e-1	1.22e-1
-113	1.12e+8	1.64e+6	5.38e+6	1.88e+6	15488	11	190	1.47e-2	3.50e-1	1.30e-2	3.59e-1	3.67e-1
-114	4.71e+7	1.12e+6	5.38e+6	3.59e+6	15488	188	915	2.37e-2	7.09e-1	7.12e-2	7.16e-1	7.36e-1
-115	1.00e+7	3.32e+5	4.22e+6	3.91e+6	15488	425	3074	3.32e-2	9.26e-1	2.26e-1	9.28e-1	9.45e-1
-116	1.72e+6	7.53e+4	2.99e+6	2.94e+6	15488	776	6221	4.38e-2	9.82e-1	4.52e-1	9.83e-1	9.91e-1
-117	1.64e+5	9.32e+3	1.72e+6	1.72e+6	15488	809	9792	5.67e-2	9.97e-1	6.84e-1	9.97e-1	9.99e-1
-118	8.45e+3	5.76e+2	7.05e+5	7.05e+5	15488	1857	11627	6.82e-2	1.00e+0	8.71e-1	1.00e+0	1.00e+0
-119	1.92e+2	1.60e+1	1.78e+5	1.78e+5	15488	6385	8598	8.33e-2	1.00e+0	9.67e-1	1.00e+0	1.00e+0
-120	0.00e+0	0.00e+0	1.97e+4	1.97e+4	15488	12368	3064	1.00e+0	1.00e+0	9.96e-1	1.00e+0	1.00e+0

Table 5-5 AS4928 FLEX measurement

Tx Power	Usable bits		Codewords (CW)		Frame Erasures			BER bits	BER CWs	BER frame	BER block	BER system
	Tot. Bits	Errored	Total CWs	Erasures	Total	An	Comma					
-100	1.74e+8	2.50e+1	5.45e+6	0.00e+0	15488	0	0	1.43e-7	0.00e+0	0.00e+0	1.43e-7	1.43e-7
-101	1.74e+8	2.50e+1	5.45e+6	0.00e+0	15488	0	0	1.43e-7	0.00e+0	0.00e+0	1.43e-7	1.43e-7
-102	1.74e+8	3.40e+1	5.45e+6	0.00e+0	15488	0	0	1.95e-7	0.00e+0	0.00e+0	1.95e-7	1.95e-7
-103	1.74e+8	3.90e+1	5.45e+6	0.00e+0	15488	0	0	2.24e-7	0.00e+0	0.00e+0	2.24e-7	2.24e-7
-104	1.74e+8	4.20e+1	5.45e+6	0.00e+0	15488	0	0	2.41e-7	0.00e+0	0.00e+0	2.41e-7	2.41e-7
-105	1.74e+8	8.40e+1	5.45e+6	0.00e+0	15488	0	0	4.81e-7	0.00e+0	0.00e+0	4.81e-7	4.81e-7
-106	1.74e+8	1.07e+2	5.45e+6	0.00e+0	15488	0	0	6.13e-7	0.00e+0	0.00e+0	6.13e-7	6.13e-7
-107	1.74e+8	3.41e+2	5.45e+6	0.00e+0	15488	0	0	1.95e-6	0.00e+0	0.00e+0	1.95e-6	1.95e-6
-108	1.74e+8	2.29e+3	5.45e+6	0.00e+0	15488	0	0	1.31e-5	0.00e+0	0.00e+0	1.31e-5	1.31e-5
-109	1.74e+8	1.62e+4	5.45e+6	2.29e+2	15488	0	0	9.26e-5	4.20e-5	0.00e+0	1.35e-4	1.35e-4
-110	1.74e+8	8.63e+4	5.45e+6	1.45e+3	15488	0	0	4.95e-4	2.67e-4	0.00e+0	7.62e-4	7.62e-4
-111	1.74e+8	3.41e+5	5.45e+6	9.47e+3	15488	0	2	1.96e-3	1.74e-3	1.29e-4	3.69e-3	3.82e-3
-112	1.71e+8	9.92e+5	5.45e+6	9.22e+4	15488	1	9	5.79e-3	1.69e-2	6.46e-4	2.26e-2	2.32e-2
-113	1.56e+8	1.93e+6	5.42e+6	5.51e+5	15488	6	96	1.24e-2	1.02e-1	6.59e-3	1.13e-1	1.19e-1
-114	1.02e+8	1.99e+6	5.20e+6	2.01e+6	15488	134	573	1.95e-2	3.86e-1	4.56e-2	3.98e-1	4.25e-1
-115	3.15e+7	8.29e+5	4.61e+6	3.62e+6	15488	196	2199	2.63e-2	7.86e-1	1.55e-1	7.92e-1	8.24e-1
-116	5.26e+6	1.91e+5	3.47e+6	3.31e+6	15488	585	5033	3.62e-2	9.53e-1	3.63e-1	9.54e-1	9.71e-1
-117	6.24e+5	3.09e+4	2.08e+6	2.06e+6	15488	1340	8233	4.94e-2	9.91e-1	6.18e-1	9.91e-1	9.97e-1
-118	3.84e+4	2.29e+3	8.99e+5	8.97e+5	15488	3330	9605	5.96e-2	9.99e-1	8.35e-1	9.99e-1	1.00e+0
-119	1.28e+3	9.70e+1	2.16e+5	2.16e+5	15488	8731	6143	7.58e-2	1.00e+0	9.60e-1	1.00e+0	1.00e+0
-120	0.00e+0	0.00e+0	1.72e+4	1.72e+4	15488	13979	1460	1.00e+0	1.00e+0	9.97e-1	1.00e+0	1.00e+0

Table 5-6 AS4927 BER versus E_b/N_o

Tx Power (dBm)	Rx Power (mW)	Eb/No (dB)	BER bits	BER system
-100	1.73E-11	23.8	1.00E-20	1.00E-20
-101	1.38E-11	22.8	5.73E-09	5.73E-09
-102	1.09E-11	21.8	5.73E-09	5.73E-09
-103	8.69E-12	20.8	3.44E-08	3.44E-08
-104	6.90E-12	19.8	2.29E-08	2.29E-08
-105	5.48E-12	18.8	5.73E-08	5.73E-08
-106	4.36E-12	17.8	3.96E-07	3.96E-07
-107	3.46E-12	16.8	2.67E-06	8.58E-05
-108	2.75E-12	15.8	1.81E-05	4.22E-04
-109	2.18E-12	14.8	1.18E-04	2.09E-03
-110	1.73E-12	13.8	5.97E-04	8.05E-03
-111	1.38E-12	12.8	2.27E-03	3.24E-02
-112	1.09E-12	11.8	6.77E-03	1.22E-01
-113	8.69E-13	10.8	1.47E-02	3.67E-01
-114	6.90E-13	9.8	2.37E-02	7.36E-01
-115	5.48E-13	8.8	3.32E-02	9.45E-01
-116	4.36E-13	7.8	4.38E-02	9.91E-01
-117	3.46E-13	6.8	5.67E-02	9.99E-01
-118	2.75E-13	5.8	6.82E-02	1.00E+00
-119	2.18E-13	4.8	8.33E-02	1.00E+00
-120	1.73E-13	3.8	1.00E+00	1.00E+00
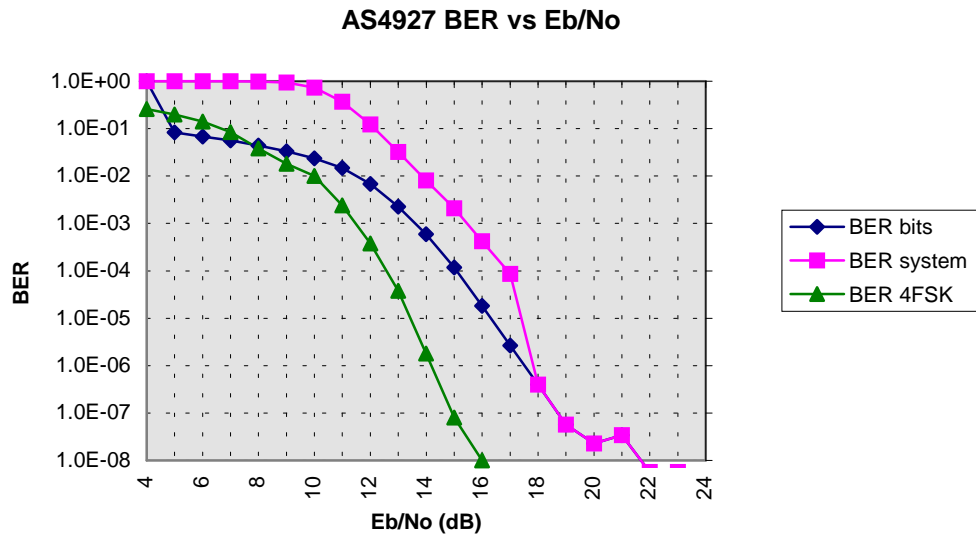
Figure 5-1 AS4927 Graph of BER versus E_b/N_o

Table 5-7 AS4928 BER versus E_b/N_o

Tx Power (dBm)	Rx Power (mW)	Eb/No (dB)	BER bits	BER system
-100	1.77E-11	23.9	1.43E-07	1.43E-07
-101	1.41E-11	22.9	1.43E-07	1.43E-07
-102	1.12E-11	21.9	1.95E-07	1.95E-07
-103	8.87E-12	20.9	2.24E-07	2.24E-07
-104	7.05E-12	19.9	2.41E-07	2.41E-07
-105	5.60E-12	18.9	4.81E-07	4.81E-07
-106	4.45E-12	17.9	6.13E-07	6.13E-07
-107	3.53E-12	16.9	1.95E-06	1.95E-06
-108	2.81E-12	15.9	1.31E-05	1.31E-05
-109	2.23E-12	14.9	9.26E-05	1.35E-04
-110	1.77E-12	13.9	4.95E-04	7.62E-04
-111	1.41E-12	12.9	1.96E-03	3.82E-03
-112	1.12E-12	11.9	5.79E-03	2.32E-02
-113	8.87E-13	10.9	1.24E-02	1.19E-01
-114	7.05E-13	9.9	1.95E-02	4.25E-01
-115	5.60E-13	8.9	2.63E-02	8.24E-01
-116	4.45E-13	7.9	3.62E-02	9.71E-01
-117	3.53E-13	6.9	4.94E-02	9.97E-01
-118	2.81E-13	5.9	5.96E-02	1.00E+00
-119	2.23E-13	4.9	7.58E-02	1.00E+00
-120	1.77E-13	3.9	1.00E+00	1.00E+00
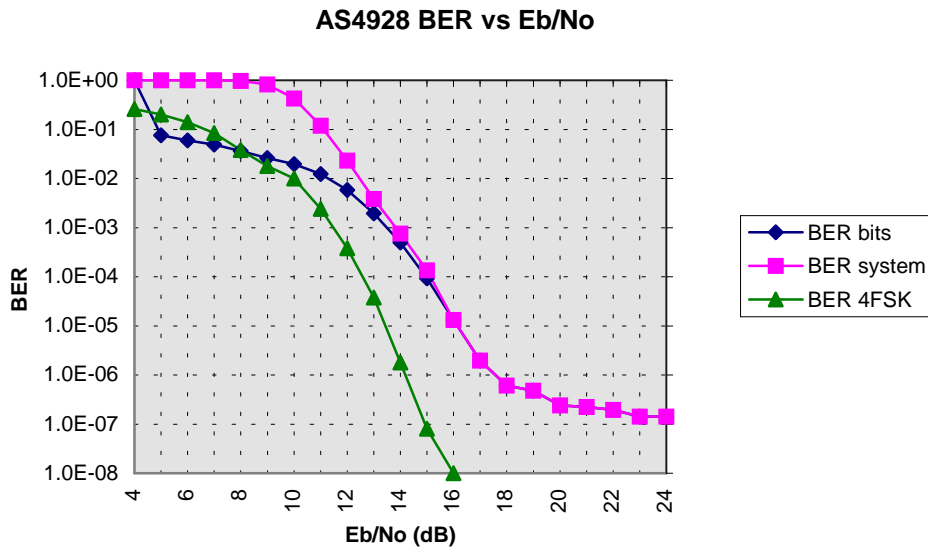
Figure 5-2 AS4928 Graph of BER versus E_b/N_o

5.5 Analysis

As Figure 5-1 and Figure 5-2 show, the difference between ideal and the system BER is between 3 and 4 dB. The reason that the bit BER (BER from usable codewords only) is better than ideal for E_b/N_o less than 8 dB is the fact the number of bit errors that can detected is 3, so the maximum possible bit BER is 9.4e-2 (3 divided by 32). The bit BER of 1.0 at E_b/N_o equal to 4 dB is when no usable codewords were decoded. The bit BER and system BER are the same for high E_b/N_o (>15 for AS4928 and >17 for AS4927). This is expected since the probability of multiple bits in error for a single codeword is extremely low. Once these diverge, the bit BER clips to its maximum value of 9.4e-2 but the system BER continues on the expected curve. The system BER is very pessimistic. The calculation of an erasure on the system BER is that the entire codeword is in error. This leads to a BER greater than 0.5. If the system BER used 50% bits in error instead of 100% for an erasure then the system BER would approach 0.5. The reason that this work chose to error the entire codeword was the fact that pagers cannot process codewords that have 0.5 BER. A pager can actually only process codewords that have 2 bits in error since it can correct those bit errors. The results are expected and simply provide a measure of the performance of the designed paging decoder.

6. Conclusion

The author's contribution-s in this work have been with the design, implementation, and verification of a FLEX paging decoder. The receiver design that is briefly discussed in this thesis is not the author's work. The design of the receiver was given so that uniform perform measurements (E_b/N_o) on the receiver/decoder pair could be made. The author designed the digital decoder and implemented all the software needed to decode a FLEX data frame. This software includes microprocessor assembly code and PC based high level code. The Appendix lists all software that the author is permitted to publish. This work also presents in a clear manner how to implement bit error rate measurements on a real system and to normalize the results using E_b/N_o so that comparison to theoretical can be performed.

The design and implementation of a practical FLEX paging decoder has been presented. The performance of the receiver decoder pair was 3 to 4 dB from ideal. The performance may actually be closer to ideal if measurement error occurred. This is especially true with the noise bandwidth calculation. If a false peak noise measurement occurred, then the noise bandwidth would be calculated as too narrow. Additional work might be needed to investigate this possible problem. The approach of using a microprocessor and a few discrete components has been shown to provide acceptable performance. Additional work to better the BER might be to examine the front end filter on the decoder to ensure that the maximum amount of usable signal is provided with the minimum amount of noise. It is the classic problem of more bandwidth gives more information but also provides more noise. Another item that needs more investigation is the symbol clock timing. The sampling clock may be accurate over one FLEX frame so that once the data in the frame is synchronized no sample clock adjustments are needed. This would prevent the sampling clock from experiencing excessive jitter that could result in slipping a symbol.

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8. Appendix - Code Listings

```cpp
/***********************************************************************/
/* Program NOISEBW.CPP
/*
/* Equivalent Noise Bandwidth Program
/*
/* Purpose: Given the file of the spectrum analzer data compute the
/* noise bandwidth.  File format is 401 lines of text.  Each
/* contains the power in dBm at that point.  The frequency span
/* of the analyzer was 50 KHz. The analyzer had 10 major divisions.
/* Each division represented 5 KHz and contained 40 points. This
/* gives 400 points so the last point is to complete the whole
/* 50 Khz span.
/*
/* The frequency at each point is 425 KHz + n * 5KHz/40.
/* n=0 gives 425 KHz (first point at beginning of sweep)
/* n=400 gives 475 MHz (last point at beginning of sweep)
/*
/* Assumption: See purpose
/*
/* Compiler: BorlandC++ version 4.52
/*
/* Scott McCulley
/* Grayson Wireless
/* Copyright 1997
/***********************************************************************/

#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <values.h>
#include <string.h>
#include <dos.h>
#include <math.h>
#include <conio.h>

#define MAX_DATA 401

/* Global variable*/
double specData[MAX_DATA];

/***********************************************************************/
/* loadSpecData
/*
/* Purpose: Load the global variable with the data from the passed in file
/***********************************************************************/
int loadSpecData(char *filename)
{
   FILE *specDataFile;

   if ((specDataFile=fopen(filename,"rt")) == NULL) {
      printf("Error file %s does not exist.\n", filename);
      return -2;
   }

   for (int i=0; i<MAX_DATA; i++) {
      fscanf(specDataFile,"%lf\n",&specData[i]);
//    printf("Data at %d is %5.3le\n",i,specData[i]);
//    getch();
   }

   fclose(specDataFile);
   return 0;
}

/***********************************************************************/
/* dbm2mW
/*
/* Purpose: Return the passed in dBm value in mW
/***********************************************************************/
double dbm2mW(double dbm)
{
   double mW;
```

```
    /* power dbm = 10 log(power mW / 1 mW) */
    /* power dbm / 10 = log(power mW / 1 mW) */
    /* 10 ^ (power dbm / 10)  mW = power mW

    /* raise dbm to 10 power  y=10^x --- ln(y) = x ln(10) ---*/
    /* y = exp( x ln(10)) ---  ln() == log()*/
    mW = exp( (dbm/10.0) * log(10.0));

    return mW;
}
/***********************************************************************/
/* calculateNoiseBw
/*
/* Purpose: Find the max value in global variable specData.  Compute total power.
/* Get width of rectangle by dividing total power by max value.
/***********************************************************************/
double calculateNoiseBw(void)
{
/* frequency =  425 KHz + n * 5KHz/40. */
    int i;
    double maxData=-1000.0, sum=0.0, bw=0.0;

    /* find max in specData */
    for (i=0;i<MAX_DATA;i++) {
       maxData = max(specData[i],maxData);
    }

    printf("The max value is %7.2lf dBm or %5.3le mW.\n",maxData,dbm2mW(maxData));

    /* integrate over entire data */
    for (i=0;i<MAX_DATA;i++) {
       sum += (dbm2mW(specData[i]) * 125);    //125 Hz = 5 KHz/ 40
    }

    printf("The integrated sum over all values is %5.3le mW Hz.\n",sum);

    bw = sum / dbm2mW(maxData);
/*
    for (i=195; i<205; i++) {
       printf("The noise bw using point %d=%7.2lf dBm is %6.0lf Hz.\n",i, specData[i],sum /
dbm2mW(specData[i]));
    }
*/
    return bw;
}

/***********************************************************************/
/* main
/*
/* Purpose: Get file name from the command line and call loadSpecData.
/* Then call calculateNoiseBw and show result.
/***********************************************************************/
void main(void)
{
    int result=0;
    double bw=0.0;
    char filename[255];

    if (_argc < 2) {
       printf("USAGE: NOISEBW [FILENAME]\n");
       result = -1;
    }

// printf("arguements 0)%s 1)%s 2)%s\n",_argv[0], _argv[1], _argv[2]);
    strcpy(filename,_argv[1]);
    printf("Filename is %s\n",filename);
    if (!result) {
       result = loadSpecData(filename);
    }

    if (!result) {
       bw=calculateNoiseBw();
       printf("The noise bw for file %s is %6.0lf Hz.\n",filename,bw);
    }

    exit(result);
}
```

```
/*************************************************
/* Program: FLEX.CPP
/*
/* Flex Random Cycle Generator for HP 8648A
/*
/* Purpose: Command line interface to preform one of the following
/*
/* USAGE: FLEX [I,R,S,E] [NUM,AMPL] [RATE]
/*   I=Initialize
/*   R=Generate new random data. Save to file FLXrxxxx.RND where r is RATE and xxxx is NUM
/*   S=Start Flex Data at give AMPLitude (negative dBm assumed) at RATE ('1'-'4')
/*   E=Stop Flex Data.
/*
/* "I" sends a set of initializations strings to HP 8648A for set-up
/*
/* "R" Generate a random flex cycle.  The frame information is unique for each
/* of the 128 frames generated.  All data codewords in the interleaved blocks are
/* randomly generate the 21 data bits and then perform BCH and even parity to complete
/* each 32-bit codeword.  Random data is saved to a file and sent to HP8648A.
/* Codewords are NOT send interleaved.  The HP8648A adds the correct SYNC1, SYNC2 and
/* handles the block interleaving.
/*
/* "S" Starts the HP8648A at a give amplitude to send the flex cycle.
/*
/* "E" Stops the HP8648A from sending the flex cycle.
/*
/* Assumption: HP 8648A on address 18. HPIB perform with National Instruments
/* PCMCIA card for DOS Version 2.7.2. AT-GPIB/TNT software used because running
/* with Windows 95 or any AT-GPIB.  Code will work also work on National Instruments
/* AT-GPIB card installed in desktop PC
/*
/* Compiler: BorlandC++ version 4.52
/*
/* Scott McCulley
/* Grayson Wireless
/* Copyright 1997
/*************************************************/

#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <values.h>
#include <string.h>
#include <dos.h>
#include "w_instr.h"          //Grayson Header file for HPIB communication

#define SENDTOHPIB;
//#define WRITEHPIBFILE        //Text file of all data sent over HPIB (debug)
//#define ECHOINFO             //Progress written to screen (debug)
#define LAST_FRAME 127         //Last frames to generate. Should be 127
//#define WRITETXT              //Text file of random FLEX data generated (debug)

/*GLOBAL VARIABLES*/
#ifdef SENDTOHPIB
   Instr hp8648a;     //Instr class.  Grayson Library Class written to
                      //communicate via HPIB.  Code not provided.
#endif

/******************************************************************************
/* function bch31_21_parity_plus_even
/*
/* Purpose: Given the 21 data bits generate the 10 parity bits and even parity
/* bit and return the 32 codeword with data in 21 MSB, bch parity in next 10 and
/* even parity in LSB
/******************************************************************************/
unsigned long bch31_21_parity_plus_even(unsigned long data)
{
const
   polynominal= 0x369;   // 11101101001b =  X^10+X^9+X^8+X^6+X^5+X^3+1

   unsigned long savedata=data,working=0;
   int i;
   if (data >= 0x200000l) { //illegal to have data > 11 bits
      exit;
   }
   for (i=0;i<21;i++) {
    working *= 2;  //shift left by one
    data *= 2; //shift left by one}
    //data in working bits 0 to 9 check bit 10
    if ( ((working >> 10) & 1) != ((data >> 21) & 1) ) {
```

```
        //bit location 0 - 20 is data 21 is check bit
        working ^= polynominal;
      }
      working &=  0x3FF;  //save only last 10 bits
      data &= 0x1FFFFFl;  //save only last 21 bits
    }
//   printf("data is %lX and parity is %lX\n",savedata,working);
     savedata = ((savedata << 11) & 0xFFFFF800l) | ((working << 1) & 0x7FE);
     //parity is in LSB of save data and it is 0
     for (i=1; i<32; i++) {
       if ((savedata >> i) & 1) {  // if bit at ith posistion is set
          savedata ^= 1;  //complement the lsb
       }
    }
    return savedata;
}


/****************************************************************************/
/* function invert
/*
/* Purpose: Given a 32 unsigned long int. Invert data bits bit 31 to bit 0,
/*    bit 30 to bit 1, etc.
/****************************************************************************/
unsigned long invert(unsigned long data)
{
    unsigned long invertedData=0;
    for (int i=0;i<32;i++) {
       invertedData |= ((data >> (31 - i)) & 1) << i;
    }
    return invertedData;
}

/****************************************************************************/
/* function sendHpib
/*
/* Purpose: Send string to hp6448a (if defined) and write to file (if defined).
/****************************************************************************/
void sendHpib(char *hpibStr)
{
#ifdef WRITEHPIBFILE
    FILE *hpib;
#endif

#ifdef SENDTOHPIB
    hp8648a.Send(hpibStr);
#endif

#ifdef WRITEHPIBFILE
    if ( (hpib=fopen("flexhpib.dat","a+t")) == NULL) {
       printf("Error output file not created.\n");
       exit(-1);
    }
    fprintf(hpib,"%s\n",hpibStr);
    fclose(hpib);
#endif
}

/****************************************************************************/
/* function initializeHP8648A
/*
/* Purpose: initialize the HP8648A with the following
/*    FREQUENCY: 930.0000 MHZ
/*    FM DEVIATION: 4.80 KHz
/*    AUTOMATC ATTENUATOR: ON
/*    AMPLITUDE: -80 dBM
/*    RF: ON
/*    DIGITAL MODULATION: ON
/*    FORMAT: FLEX
/*    POLARITY: NORMAL
/*    FILTER: ON
/*    MESSAGE NUMBER: 0
/*    START FRAME: 0
/*    STOP FRAME: 127
/*    MODE: CONT
/*    IMMEDIATE STOP: ON
/*
/****************************************************************************/
void initializeHP8648A(void)
{
```

```
   char hpibStr[255];
   //from Chapter 2 in HP8648A manual

   sprintf(hpibStr,"FREQ:CW 930.00000 MHZ");
   sendHpib(hpibStr);

   sprintf(hpibStr,"DM:DEV 4.8 KHZ");
   sendHpib(hpibStr);

   sprintf(hpibStr,"POW:ATT:AUTO ON");
   sendHpib(hpibStr);

   sprintf(hpibStr,"POW:AMPL -80 dBm");
   sendHpib(hpibStr);

   sprintf(hpibStr,"OUTP:STAT ON");
   sendHpib(hpibStr);

   sprintf(hpibStr,"DM:STAT ON");
   sendHpib(hpibStr);

   sprintf(hpibStr,"PAG:SEL FLEX");
   sendHpib(hpibStr);

   sprintf(hpibStr,"DM:POL NORM");
   sendHpib(hpibStr);

   sprintf(hpibStr,"DM:FILT:STAT ON");
   sendHpib(hpibStr);

   sprintf(hpibStr,"PAG:FLEX:MESS:SEL 0");
   sendHpib(hpibStr);

   sprintf(hpibStr,"PAG:FLEX:ARB:STAR 0");
   sendHpib(hpibStr);

   sprintf(hpibStr,"PAG:FLEX:ARB:STOP %d",LAST_FRAME);
   sendHpib(hpibStr);

   sprintf(hpibStr,"TRIG:COUN 0");   //trigger count 0 is continous mode
   sendHpib(hpibStr);

   sprintf(hpibStr,"PAG:FLEX:IST:STAT ON");
   sendHpib(hpibStr);

   delay(1000);
}
/****************************************************************************/
/* function startFlex
/*
/* Purpose: send tp the HP8648A with the following
/*     AMPLITUDE: inputted amplitudeStr (amp in dBm with negative sign implide
/*     FORMAT: FLEX
/*     DATA RATE: 6400/4, 3200/4, 3200/2, 1600/2 based on inputted rate char
/*     START ENCODING
/****************************************************************************/
void startFlex(char *amplitudeStr, char rate)
{
   char hpibStr[255], rateStr[10], fskStr[10];
   //from Chapter 2 in HP8648A manual

   sprintf(hpibStr,"POW:AMPL -%s dBm", amplitudeStr);
   sendHpib(hpibStr);

   switch (rate) {
      case '4':
         strcpy(rateStr,"6400");
         strcpy(fskStr,"FSK4");
         break;
      case '3':
         strcpy(rateStr,"3200");
         strcpy(fskStr,"FSK4");
         break;
      case '2':
         strcpy(rateStr,"3200");
         strcpy(fskStr,"FSK2");
         break;
      case '1':
         strcpy(rateStr,"1600");
```

```
                strcpy(fskStr,"FSK2");
                break;
          default:
                printf("Error Rate not valid.\n");
#ifdef SENDTOHPIB
                hp8648a.Close();
                hp8648a.CloseAll();
#endif
                exit(-1);
      }

      sprintf(hpibStr,"PAG:FLEX:RATE %s",rateStr);
      sendHpib(hpibStr);

      sprintf(hpibStr,"DM:FORM %s",fskStr);
      sendHpib(hpibStr);

      delay(2000);

      sprintf(hpibStr,"INIT:IMM");
      sendHpib(hpibStr);
}

typedef struct {
      unsigned long int frameInfo;
      unsigned long int blockData[352];
      } flexBlock;

/****************************************************************************/
/* function writeRandomArb
/*
/* Purpose: send tp the HP8648A with the following
/*    DIGITAL MODULATION: ON
/*    FORMAT: FLEX
/*    DATA RATE: 6400/4, 3200/4, 3200/2, 1600/2 based on inputted rate char
/*    MESSAGE NUMBER: 0
/*
/****************************************************************************/
void writeRandomArb(char *numStr, char rate)
{
#ifdef WRITETXT
   FILE *textFile;
#endif
   FILE *binFile;
   int i,frame=0, maxCw;
   unsigned long lsb14,msb7;
   unsigned long flexData, frameInfo;
   flexBlock *pFlexBlock;
   char s[255], fileNameStr[255];
   char hpibStr[255], rateStr[10], fskStr[10];
   //from Chapter 2 in HP8648A manual

   switch (rate) {
      case '4':
         strcpy(rateStr,"6400");
         strcpy(fskStr,"FSK4");
         maxCw = 352;
         break;
      case '3':
         strcpy(rateStr,"3200");
         strcpy(fskStr,"FSK4");
         maxCw = 176;
         break;
      case '2':
         strcpy(rateStr,"3200");
         strcpy(fskStr,"FSK2");
         maxCw = 176;
         break;
      case '1':
         strcpy(rateStr,"1600");
         strcpy(fskStr,"FSK2");
         maxCw = 88;
         break;
      default:
         printf("Error Rate not valid.\n");
#ifdef SENDTOHPIB
         hp8648a.Close();
         hp8648a.CloseAll();
#endif
         exit(-1);
```

```
    }

    sprintf(hpibStr,"PAG:FLEX:RATE %s",rateStr);
    sendHpib(hpibStr);

    sprintf(hpibStr,"DM:FORM %s",fskStr);
    sendHpib(hpibStr);

    delay(1000);

    randomize();
#ifdef WRITETXT
    sprintf(fileNameStr,"..\\data\\flx%c%s.TXT",rate,numStr);
    if ( (textFile=fopen(fileNameStr,"wt")) == NULL) {
       printf("Error text output file %s not created.\n", fileNameStr);
       exit(-1);
    }
#endif

    sprintf(fileNameStr,"..\\data\\flx%c%s.RND",rate,numStr);
    if ( (binFile=fopen(fileNameStr,"wb")) == NULL) {
       printf("Error binary output file %s not created.\n", fileNameStr);
       exit(-1);
    }

    //from page 2-26 in HP8648A manual
    //lsb16 = 0 msb16=16926 : cycle 0 frame 0 collapse 0 repeat 0 t 0xF

    pFlexBlock = new (flexBlock);

    while (frame <= LAST_FRAME)
    {
#ifdef ECHOINFO
       printf("Forming and sending flex frame %d\n", frame);
#endif

#ifdef SENDTOHPIB
       hp8648a.EnableEOT(0);
#endif
       //FI = xxxx 0000 ffff fff0 0000 0    c=0, n=0, r=0, t=0
       //xxxx = 1's complement fff0 + ffff
       lsb14 = (frame & 0xF) + ((frame >> 4) & 0x7);
       lsb14 = (lsb14 ^ 0xF) & 0xF;
       msb7 = ((frame << 8) & 0x7F00) | lsb14;
       frameInfo = (invert(msb7) >> 11);
//     printf("frame: %d, x is 0x%04lX, fi is 0x%06lX invert fi is 0x%06lX\n", frame, lsb14, msb7,
frameInfo);
       frameInfo = bch31_21_parity_plus_even(frameInfo);
       frameInfo = invert(frameInfo);
//   frameInfo is equal to ((unsigned long)(16926) << 16) & (unsigned long)(0xFFFF0000)
//     printf("Frame Info %08lX\n",frameInfo);

       sprintf(hpibStr,"PAG:FLEX:ARB:DEF");
       sprintf(s," %d, %d",frame, (frameInfo >> 16) & 0xFFFF);
       strcat(hpibStr,s);
       sprintf(s, ", %d", frameInfo & 0xFFFF);
       strcat(hpibStr,s);
#ifdef WRITETXT
       fprintf(textFile,"FRAME %03d\n",frame);
       fprintf(textFile,"FI=%08lX\n",frameInfo);
#endif
       pFlexBlock->frameInfo = frameInfo;

       for (i=0; i<maxCw; i++)
       {
          sendHpib(hpibStr);
          strcpy(hpibStr,"");

          lsb14 = random(0x4000);    //return random number between 0 and 0x3FFF
          msb7 = random(0x80);   //return random number between 0 and 0x7F
          flexData = (msb7 << 14) | lsb14;
//       printf("lsb14 %lX msb7 %lX flexdata %08lX\n", lsb14, msb7, flexData);
          flexData = bch31_21_parity_plus_even(flexData);
          flexData = invert(flexData);
       //had problem with Borland the msb and lsb conversion of flexData could not
       //be done on the same line
          sprintf(s, ", %d", (flexData >> 16) & 0xFFFF );
          strcat(hpibStr,s);
          sprintf(s, ", %d", flexData & 0xFFFF );
          strcat(hpibStr,s);
```

```
/*         printf("flex %08lX = msb16 %04lX lsb16 %04lX  ", flexData,
               (flexData >> 16) & 0xFFFF, flexData & 0xFFFF );
           printf("Decimal MSB %d, ", ((flexData >> 16) & 0xFFFF) );
           printf("LSB %d\n", (flexData & 0xFFFF) );
*/
#ifdef WRITETXT
         fprintf(textFile,"%08lX\n",flexData);
#endif
           pFlexBlock->blockData[i] = flexData;
        }

#ifdef ECHOINFO
      printf("Completed flex frame %d\n", frame);
#endif

        if (fwrite(pFlexBlock, sizeof(flexBlock), 1, binFile)!=1) {
           printf("Error can not write to binary output file.\n");
           exit(-1);
        }

#ifdef SENDTOHPIB
      hp8648a.EnableEOT(1);
#endif
        sendHpib(hpibStr);
        frame++;
    }

    delete(pFlexBlock);

#ifdef WRITETXT
   fclose(textFile);
#endif
   fclose(binFile);

   delay(2000);   //wait 0.5 second so that data is processed
}

/*****************************************************************************/
/* function stopEncoding
/*
/* Purpose: send tp the HP8648A with the following
/*          STOP ENCODING
/*
/*****************************************************************************/
void stopEncoding(void)
{
   char hpibStr[255];
   //from Chapter 2 in HP8648A manual

   sprintf(hpibStr,"ABOR");
   sendHpib(hpibStr);
}

/*****************************************************************************/
/* function main
/*
/* Purpose: Examine command line parameters and call appropriate function
/*
/*****************************************************************************/
void main(void)
{
   int result=0;
#ifdef SENDTOHPIB
   hp8648a.Init(19);
#endif

   if (_argc < 2) {
      printf("USAGE: FLEX [I,R,S,E] [NUM,AMPL] [RATE]\n");
      printf("   I=Initialize\n");
      printf("   R=Generate new random data. Save to file FLXrxxxx.RND where r is RATE and xxxx
is NUM\n");
      printf("   S=Start Flex Data at give AMPLitude (negative dBm assumed) at RATE ('1'-
'4')\n");
      printf("   E=Stop Flex Data.\n");
      result = -1;
   }

   if (!result)
   switch (_argv[1][0]) {
```

```
        case 'I':
            initializeHP8648A();
            break;
        case 'R':
            if (_argc<2) {
                printf("Error File Number not given.\n");
                result = -1;
                break;
            }
            if (_argc<3) {
                printf("Error Rate not given.\n");
                result = -1;
                break;
            }
            writeRandomArb(_argv[2],_argv[3][0]);
            break;
        case 'S':
            if (_argc<2) {
                printf("Error Amplitude not given.\n");
                result = -1;
                break;
            }
            if (_argc<3) {
                printf("Error Rate not given.\n");
                result = -1;
                break;
            }
            startFlex(_argv[2],_argv[3][0]);
            break;
        case 'E':
            stopEncoding();
            break;
        default:
            printf("Error invalid usage.\n");
            result = -1;
    }

#ifdef SENDTOHPIB
    hp8648a.Close();
    hp8648a.CloseAll();
#endif

    exit(result);
}
```

```
/************************************************/
/* Program: ANALZER.CPP
/*
/* Flex BER Analyzer 8648A
/*
/* Purpose: Compare FLEXxxxx.RND files with mesaure data, where xxxx is a number
/* between 0000 and 9999. This number is used to identify which random sequence
/* was used in FLEX transmission. The measure data files are of the format
/* RrFfxxxx.aaa where r is the receiver number (1 to 4), f is the flex data rate
/* (1=1600-2FSK, 2=3200-2FSK, 3=3200-4FSK, 4=6400-4FSK), xxxx is the random sequence
/* received, and aaa is amplitude of generator (range 090 to 120 negative sign remove).
/*
/* Assumption: files FLEXxxxx.RND generated by file FLEX.EXE and files RrFfxxxx.aaa
/* collected with Pagetracker Pro Version 3.23.20 with _BERTEST_ defined in
/* standards.inc
/*
/* Compiler: BorlandC++ version 4.52
/*
/* Scott McCulley
/* Grayson Wireless
/* Copyright 1997
/************************************************/
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <values.h>
#include <string.h>
#include <dos.h>
#include <conio.h>

/* 128 exact data contents for files FLEXxxxx.RND */
typedef struct {
    unsigned long int frameInfo;
    unsigned long int blockData[352];
    } flexBlock;

/* from 0 to 128 of this data structure for files RrFfxxxx.aaa */
typedef struct {
    unsigned char rate;              //0=1600-2, 1=3200-2, 2=3200-4, 3=6400-4
    unsigned char An_Errs[2];        //Bit errors for each pattern in sync1 detected
    unsigned long int frameInfo;     //Data in bits 20-0, errored bits in bits 22-21
    unsigned char C_Errs[2];         //Bit errors for each pattern in sync2 detected
    unsigned long int blockData[352]; //Data in bits 20-0, errored bits in bits 22-21
    unsigned char result;            //0=Frame OK, 1 =Frameinfo errored, 4=comma errored,
                                     //5=comma* errored
    } measuredFlexBlock;

/* results */
typedef struct {
    double usableCodewordBits[2]; //0=total bits, 1=errored bits
    double codewordErasures[2];   //0=total codewords, 1=erasure cw
    double frameErasures[3];      //0=total frames, 1=erasure from An,
                                  //2=errors from comma
//Total frames is always 128
//Total codewords is always (TotalFrames-erasures) * 352
//Total bits is always (TotalCodewords-erasures) * 32
    } resultsFlexBlock;

/* Global Variables */
    flexBlock *pFlexCycle[128];  //one flex cyle is 128 flex frames
    unsigned char rxUsed[4][4];       //1st[4] is receiver, 2nd[4] is rate.
                                      //initialized to 1 once RrFfxxxx.aaa is not found
                                      //see to 0 so if not processed any more
    resultsFlexBlock results[4][4][31];   //1st[4] is receiver 0-3,
                                      //2nd[4] is rate where 0=1600-2FSK,
                                      //1=3200-2FSK, 2=3200-4FSK, 3=6400-4FSK,
                                      //[31] is dbm where 0=90dBm,
                                      //1=91dBm, ... 30=120dBm

#define START_DBM 0        //should be 0
#define STOP_DBM 20        //should be 30 for (-90 to -120) or 20 for (-100 to -120)
#define DBM_OFFSET 100     //offset to bring START_DBM to actual dbm should be 90
                           // or 100(negative implided)
#define START_FRAME 0      //should be 0
#define STOP_FRAME 127     //should be 127
#define START_NUM 0        //should be 0
#define STOP_NUM 9999      //should be 9999
#define START_RX 0         //should be 0
#define STOP_RX 3          //should be 3
#define DISPLAY_DBM -105   //all dbm less than this value will display errors
```

```
                          //TRACE_02 to _04

//below are trace statements that are enabled if the trace number is not zero
//these are only for debug purposes.  The needch for some of the traces requires
//a user to press a key to continue the program.
int TRACE_01=  0;          //trace frame number, frame read, FI, rx frame
int TRACE_02=  0;          //trace BCH errors
int NEEDCH_02= 0;          //need ch to continue after BCH error
int TRACE_03=  0;          //trace comma errors
int NEEDCH_03= 0;          //need ch to continue after comma error
int TRACE_04=  0;          //Trace erasures codewords
int NEEDCH_04= 0;          //need ch to continue after cw erasure
int TRACE_05=  1;          //Trace extra data in file
int NEEDCH_05= 0;          //after extra data in file
int NEEDCH_06= 0;          //Every 9 frames wait for user input
int TRACE_07=  0;          //trace missed frames
int NEEDCH_07= 0;          //need ch to continue after missed frame
int TRACE_08=  0;          //trace erasures that have no BCH error
int NEEDCH_08= 0;          //need ch to continue erasure w/ no BCH errs
int TRACE_09=  0;          //trace Frame Info problems
int NEEDCH_09= 0;          //need ch to continue after frame info problems


/*prototypes*/
void allocateAndInitVars(void);
void freeMemory(void);

/************************************************
/* masterExists
/*
/* Purpose: returns 1 if file exists otherwise return 0
/* File name is based on numStr and rateCh
/***********************************************/
int masterExists(char *numStr, char rateCh)
{

   FILE *binFile;
   char fileNameStr[255];

   sprintf(fileNameStr,"..\\data\\FLX%c%s.RND",rateCh,numStr);
   if ( (binFile=fopen(fileNameStr,"rb")) == NULL) {
//    printf("Error binary output file %s does not exist.\n", fileNameStr);
      return(0);
   }

   fclose(binFile);

   return(1);
}

/************************************************
/* loadMaster
/*
/* Purpose: Fills the global variable pFlexCycle with data in master file that
/* contains frameinfo and random codewords sent by HP8648A for this number and rate
/***********************************************/
int loadMaster(char *numStr, char rateCh)
{
   FILE *binFile;
   char fileNameStr[255];
   int frame=START_FRAME;
//   int cw;

   sprintf(fileNameStr,"..\\data\\FLX%c%s.RND",rateCh,numStr);
   if ( (binFile=fopen(fileNameStr,"rb")) == NULL) {
      printf("Error binary output file %s does not exist.\n", fileNameStr);
      return(-1);
   }

   while (frame <= STOP_FRAME) {
      if (fread(pFlexCycle[frame], sizeof(flexBlock), 1, binFile)!=1) {
         printf("Error can not read frame %d from %s.\n", frame, fileNameStr);
         fclose(binFile);
         return(-1);
      }
/*
      for (cw=0;cw<352;cw++) {
         if ( (pFlexCycle[frame]->blockData[cw] & 0x1FFFFFl) == 0x053FE7l) {
            printf("Num:%s Frame:%d cw:%d is %06lX\n",numStr, frame, cw, (pFlexCycle[frame]-
>blockData[cw] & 0x1FFFFFl));
```

```
                printf("Num:%s Frame:%d cw:%d is %06lX\n",numStr, frame-1, cw, (pFlexCycle[frame-1]-
>blockData[cw] & 0x1FFFFFl));
            }
        }
*/
        frame++;
    }
    fclose(binFile);

    return(0);
}

/*************************************************
/* berResult
/*
/* Purpose: Return 1 if data is ok.  Otherwise return -1.
/* For the number specificed, the rate and amplitude is traversed through.
/* Only one rate is processed (3=6400-4).  The file that the PAGETRACKER Pro software
/* logged for each amplitude is examined.  Results are tallied in global variable results
/*************************************************/
int berResult(char *numStr)
{
/* RrFfxxxx.aaa where r is the receiver number (1 to 4), f is the flex data rate
   (1=1600-2FSK, 2=3200-2FSK, 3=3200-4FSK, 4=6400-4FSK), xxxx is the random sequence
   received, and aaa is amplitude of generator (range 090 to 120 negative sign remove). */

    FILE *binFile;
    char fileNameStr[255], amplitudeStr[4], rateCh, rxNumCh, ch=' ';
    int rate, frame=START_FRAME, cw, rxFrame, rxNum, framesRead=0, fCount,displayCount, lastCount;
    int dbm;
    int infoDisplayed=0;
    unsigned char cont;
    measuredFlexBlock rxFlexBlock;

 for (rate=0; rate<4; rate++) {
  cont=1;  //assume continue
  for (rxNum=START_RX; rxNum<=STOP_RX; rxNum++)
   if (rxUsed[rxNum][rate])  //if all receiver are not used then continue in loop
     cont=0;                  //this receive is used so no continue statement
  if (cont)  //if all receivers not used continue in loop
     continue;

  rateCh = '1'+(char)(rate);
  if (loadMaster(numStr, rateCh) == 0) {
     printf("Analazing number %s rate %c\n",numStr, rateCh);
  }
  else {
    for (rxNum=START_RX; rxNum<=STOP_RX; rxNum++) {
      rxUsed[rxNum][rate]=0; //all receivers at this rate are not used continue in loop
    }
    continue;
  };

  for (rxNum=START_RX; rxNum<=STOP_RX; rxNum++) {
   if (!rxUsed[rxNum][rate]) {  //if receiver not used continue in loop
     continue;
   }
   dbm=START_DBM;
   rxNumCh = '1'+(char)(rxNum);
   printf("Receiver %c rate %c ",  rxNumCh, rateCh);

   while (dbm <= STOP_DBM) {
      sprintf(amplitudeStr,"%03d",dbm+DBM_OFFSET);
      sprintf(fileNameStr,"..\\data\\R%cF%c%s.%s",rxNumCh,rateCh,numStr,amplitudeStr);
      if ( (binFile=fopen(fileNameStr,"rb")) == NULL) {
         printf("not used because file %s does not exist.\n", fileNameStr);
//       return(-1);
         rxUsed[rxNum][rate] = 0;  //RrFfxxxx.aaa is not found so set to false
         dbm = STOP_DBM+1;
         continue;
      }

      if (dbm == START_DBM) {
         printf("proccessing.\n");
      }

      frame=START_FRAME;
      framesRead=0;
      fCount = 0;
      displayCount=0;
```

```
        while (fCount < (STOP_FRAME-START_FRAME+1)) {
            if (TRACE_01) printf("Frame:%d Frame Read:%d Frame Count:%d ", frame,framesRead,fCount);
            if (fread(&rxFlexBlock, sizeof(measuredFlexBlock), 1, binFile)!=1) {
                if (TRACE_01) printf("Can not read %d frame(s) from %s.\n", (STOP_FRAME-
START_FRAME+1-fCount), fileNameStr);
//          getch();

                while (fCount < (STOP_FRAME-START_FRAME+1)) {
                    results[rxNum][rate][dbm].frameErasures[0]++;  //total frames
                    results[rxNum][rate][dbm].frameErasures[1]++;  //erasure by An
                    if (TRACE_07) printf("Missed frame %d\n", frame);
                    if (NEEDCH_07) getch();
                    frame++;
                    if (frame>STOP_FRAME) frame = START_FRAME;
                    fCount++;
                }
                continue;
            }
            else {
                //because HP8648A TX is not settled for first frame ignore this frame
                //this frame will be processed after frame 127 is received
                if ( (frame == START_FRAME) && (framesRead==0) ) {
                    if (TRACE_01) printf("1st frame ignored\n");
                    frame++;
                    if (frame>STOP_FRAME) frame = START_FRAME;
                    framesRead++;
                    continue;
                }

                framesRead++;
                fCount++;
                if (fCount > (STOP_FRAME-START_FRAME+1)) {
                    if (TRACE_05) printf("Extra data in file %s.\n", fileNameStr );
                    if (NEEDCH_05) getch();
                    continue;
                }

                rxFrame = int ((rxFlexBlock.frameInfo >> 8) & 0x7F);
                if (TRACE_01) printf("FI:%08lX rxFrame:%d\n", rxFlexBlock.frameInfo, rxFrame );
                if (ch=='s') ch=getch();

                if ((frame != rxFrame) && ((rxFlexBlock.result == 0) || (rxFlexBlock.result == 4)
                    || (rxFlexBlock.result == 5)) ) {
                    //here rxFrame is valid to use
//          printf("dBm:%d; Num:%s; On frame %d; rx frame %d; Frame Read %d; Frame Count
%d.\n", -(dbm+DBM_OFFSET), numStr, frame, rxFrame, framesRead, fCount );
// frame information has 3 errors they invalidate or if frame is less than excepted frame except
for frame 0
                    if ( (((rxFlexBlock.frameInfo >> 21) & 0x3)==3) ||
                        (((framesRead > rxFrame) || (rxFrame < frame)) && (rxFrame !=0)) ) {
                        if (TRACE_09) {
                            printf("dBm:%d; Invalid FI=%08lX; errs=%ld; rx frame=%d Frame Read=%d Frame
Count=%d\n", -(dbm+DBM_OFFSET), rxFlexBlock.frameInfo,
                                ((rxFlexBlock.frameInfo >> 21) & 0x3), rxFrame, framesRead, fCount );
                        }
                        if (NEEDCH_09) getch();
                        rxFlexBlock.result = 1;  //make this invalid FI
                    }
                }

                results[rxNum][rate][dbm].frameErasures[0]++;  //total frames
                if (rxFlexBlock.result > 0) {
                    //result = 1 then Frameinfo errored. 4=comma errored, 5=comma* errored
                    if (rxFlexBlock.result > 3) {
                        lastCount=fCount;
                        while ( (frame != rxFrame) && (fCount < (STOP_FRAME-START_FRAME+1)) ) {
                            results[rxNum][rate][dbm].frameErasures[0]++;  //total frames
                            results[rxNum][rate][dbm].frameErasures[1]++;  //erasure by An
                            if (TRACE_07) printf("Missed frame %d\n", frame);
                            if (NEEDCH_07) getch();
                            frame++;
                            if (frame>STOP_FRAME) frame = START_FRAME;
                            fCount++;
                        }
                        if  (fCount > (STOP_FRAME-START_FRAME+1)) {
                            continue;
                        }
                        if ((TRACE_01) && (lastCount!=fCount))printf("Now Frame:%d Frame Read:%d Frame
Count:%d FI:%08lX rxFrame:%d\n", frame,framesRead,fCount,rxFlexBlock.frameInfo, rxFrame);
```

```
                            results[rxNum][rate][dbm].frameErasures[2]++;  //erasure by Comma
                            if (( (-(dbm+DBM_OFFSET)) > (DISPLAY_DBM)) && (TRACE_03)) {
                                printf("dBm:%d; Frame %d erased by comma.\n", -(dbm+DBM_OFFSET), frame);
                                if (NEEDCH_03) getch();
                            }
                        }
                        else {
                            results[rxNum][rate][dbm].frameErasures[1]++;  //erasure by An
                            if (TRACE_07) printf("Frame %d erased by Corrupt FI.\n", frame);
                            if (NEEDCH_07) getch();
                        }
                    }
                    else {
                        //adjust frame count and frame to match current received frame
                        if (rxFlexBlock.result == 0) {
                            // e.g. FRAME 034  FI=FDA0220B //
                            lastCount=fCount;
                            while ( (frame != rxFrame) && (fCount < (STOP_FRAME-START_FRAME+1)) ) {
                                results[rxNum][rate][dbm].frameErasures[0]++;  //total frames
                                results[rxNum][rate][dbm].frameErasures[1]++;  //erasure by An
                                if (TRACE_07) printf("Missed frame %d\n", frame);
                                if (NEEDCH_07) getch();
                                frame++;
                                if (frame>STOP_FRAME) frame = START_FRAME;
                                fCount++;
                            }
                            if  (fCount > (STOP_FRAME-START_FRAME+1)) {
                                continue;
                            }
                            if ((TRACE_01) && (lastCount!=fCount))printf("Now Frame:%d Frame Read:%d Frame
Count:%d FI:%08lX rxFrame:%d\n", frame,framesRead,fCount,rxFlexBlock.frameInfo, rxFrame);
                        }

                        //here valid frame examine codewords
                        frame=rxFrame;
                        results[rxNum][rate][dbm].codewordErasures[0] += 352;  //total codeword in flex
frame
                        infoDisplayed=0;
                        ch=' ';
                        for (cw=0;cw<352;cw++) {
                            if ( (rxFlexBlock.blockData[cw] & 0x1FFFFFl) ==
                                 (pFlexCycle[frame]->blockData[cw] & 0x1FFFFFl) ) {
                                results[rxNum][rate][dbm].usableCodewordBits[0] += 32;  //total bits
                                results[rxNum][rate][dbm].usableCodewordBits[1] += (double)
                                    ( (rxFlexBlock.blockData[cw] >> 21) & 0x3);  //error bits
                                if (infoDisplayed) {
//                                  printf("%d.\n", cw-1);
                                    infoDisplayed=0;
                                }
                                if ( ( (rxFlexBlock.blockData[cw] >> 21) & 0x3) > 0) {
                                    if (( (-(dbm+DBM_OFFSET)) > (DISPLAY_DBM) ) && (TRACE_02)) {
                                        printf("dBm:%d; frame:%d; cw %d has %ld errors.\n", -(dbm+DBM_OFFSET),
frame, cw, (rxFlexBlock.blockData[cw] >> 21) & 0x3);
                                        if (NEEDCH_02) getch();
                                    }
                                }

                            }
                            else {
                                results[rxNum][rate][dbm].codewordErasures[1]++;  //erasured codeword
                                if (( ( (-(dbm+DBM_OFFSET)) > (DISPLAY_DBM) ) && (ch != 'c') && (TRACE_04)){
                                    printf("dBm %d; Frame %d; cw %d erasured; rxCw:%06lX rxErr:%ld
randCw:%06lX\n", -(dbm+DBM_OFFSET),rxFrame, cw, (rxFlexBlock.blockData[cw] & 0x1FFFFFl),
(rxFlexBlock.blockData[cw] >> 21) & 0x3,(pFlexCycle[frame]->blockData[cw] & 0x1FFFFFl));
                                    if (NEEDCH_04) ch = getch();
                                }

                                if (TRACE_08 && ( ((rxFlexBlock.blockData[cw] >> 21) & 0x3) == 0)) {
//error bits
                                    printf("Eras w/ no errs. frame:%d cw:%d rx:%08lX <> rand:%08lX
XOR:%08lX\n",
                                        frame, cw, rxFlexBlock.blockData[cw], pFlexCycle[frame]-
>blockData[cw],
                                    rxFlexBlock.blockData[cw] ^ (pFlexCycle[frame]->blockData[cw] & 0x1FFFFFl) );
                                    if ((NEEDCH_08) && (ch!='c')) ch = getch();
                                };

                                if (!infoDisplayed) {
//                                  printf("dBm %d; Frame %d; cw %d to ", -(dbm+DBM_OFFSET),rxFrame, cw);
                                    infoDisplayed=1;
```

```
                            }
                        }
                    }
                    if (infoDisplayed) {
//                      printf("%d.\n", cw-1);
                        infoDisplayed=0;
                    }
                }
/*              if ((rxFlexBlock.result == 0) || (rxFlexBlock.result == 4)
                    || (rxFlexBlock.result == 5)) */
                {
                    frame++;
                    if (frame>STOP_FRAME) frame = START_FRAME;
                }
                if ( (NEEDCH_06) && (fCount>displayCount) ) {
                    printf("Press any key to continue\n");
                    getch();
                    displayCount=fCount+8;
                }
            }
        }

        fclose(binFile);
        dbm++;
    }
  }   // end rxNum for loop
 } // end rate for loop
    return(1);

}

/***********************************************
/* safeDivide
/*
/* Purpose: If numerator is 0 then return 1 is denominator is also 0 otherwise return 0.
/* If numerator not 0 and denominator is 0 then return 1 otherwise return denominator/numerator.
/***********************************************/
double safeDivide(double num, double denom)
{
    if (num==0.0)
        if (denom==0.0)
            return 1.0;
        else
//      return 1e-16;
            return 0.0;
    else
        if (denom==0.0)
            return 1.0;
        else
            return (num / denom);
}

/***********************************************
/* saveResults
/*
/* Purpose: Write the values in global variable results to a text file.
/***********************************************/
void saveResults(void)
{
    int dbm;
    int rate;
    int rxNum;
    double bitsBer=0.0,cwErr=0.0,frameErr=0.0, blockBer=0.0, systemBer=0.0;
    char fileNameStr[255];
    FILE *txtFile;

 for (rate=0; rate<4; rate++) {
    for (rxNum=START_RX; rxNum<=STOP_RX; rxNum++) {
        dbm=START_DBM;
        if ( !results[rxNum][rate][dbm].frameErasures[0]) {
            continue;       //if no frames collected write not result file
        }
        sprintf(fileNameStr,"..\\result\\R%cF%cRSLT.TXT",'1'+(char)(rxNum), '1'+(char)(rate) );

        if ( (txtFile=fopen(fileNameStr,"wt")) == NULL) {
            printf("Error text output file %s does not exist.\n", fileNameStr);
            txtFile = stdout;
        }
```

```
        printf("Saving results for receiver %c rate %c\n",'1'+(char)(rxNum), '1'+(char)(rate));
        fprintf(txtFile,"Receiver %c rate %c\n",'1'+(char)(rxNum), '1'+(char)(rate));
        fprintf(txtFile,
" Tx | Usable CW bits  |Codeword Erasures| Fame Erasures  | BER  | BER  | BER  | BER  |
BER   \n");
        fprintf(txtFile,
//"Powr|Tot.Bits|Errored |Tot. CWs|Erasures| Total  | An   | Comma|\n");
"Powr|Tot.Bits|Errored |Tot. CWs|Erasures| Tot | An |Comma| bits  | CWs   | frame | block |
system \n");
        for (dbm=START_DBM;dbm<=STOP_DBM;dbm++) {
            bitsBer =
safeDivide(results[rxNum][rate][dbm].usableCodewordBits[1],results[rxNum][rate][dbm].usableCodewo
rdBits[0]);
            cwErr =
safeDivide(results[rxNum][rate][dbm].codewordErasures[1],results[rxNum][rate][dbm].codewordErasur
es[0]);
            frameErr =
safeDivide(results[rxNum][rate][dbm].frameErasures[1]+results[rxNum][rate][dbm].frameErasures[2],
results[rxNum][rate][dbm].frameErasures[0]);
            blockBer =
safeDivide(results[rxNum][rate][dbm].usableCodewordBits[1]+results[rxNum][rate][dbm].codewordEras
ures[1]*32.0,results[rxNum][rate][dbm].codewordErasures[0]*32.0);
            systemBer =
safeDivide(results[rxNum][rate][dbm].usableCodewordBits[1]+results[rxNum][rate][dbm].codewordEras
ures[1]*32.0+
((results[rxNum][rate][dbm].frameErasures[1]+results[rxNum][rate][dbm].frameErasures[2])*352.0*32
.0),results[rxNum][rate][dbm].frameErasures[0]*352.0*32.0);


            fprintf(txtFile,"-
%03d|%8.2le|%8.2le|%8.2le|%5.0lf|%5.0lf|%5.0lf|%8.2le|%8.2le|%8.2le|%8.2le|%8.2le\n",
(dbm+DBM_OFFSET),results[rxNum][rate][dbm].usableCodewordBits[0],
results[rxNum][rate][dbm].usableCodewordBits[1],
results[rxNum][rate][dbm].codewordErasures[0],results[rxNum][rate][dbm].codewordErasures[1],
results[rxNum][rate][dbm].frameErasures[0],results[rxNum][rate][dbm].frameErasures[1],
results[rxNum][rate][dbm].frameErasures[2],bitsBer,cwErr,frameErr,blockBer, systemBer);


        }

        fclose(txtFile);
    } //end for rxNum loop
  } //end for rate loop
}

/************************************************
/* main
/*
/* Purpose: Allocate memory and initialize variables. Loop through all randomally
/* generated cycle and call berResults.  Call saveResults to write to a file.
/************************************************/
void main(void)
{
    char* numStr="0000";
    int num;
// int rate, rxNum;
    unsigned char brk=0; //no break

    allocateAndInitVars();

    for (num=START_NUM;num<=STOP_NUM;num++) {
        sprintf(numStr,"%04d",num);
        if (masterExists(numStr, '1') || masterExists(numStr, '2') ||
             masterExists(numStr, '3') || masterExists(numStr, '4') ) {
            berResult(numStr);
/*          old way
            brk=1;  //assume break
            for (rxNum=START_RX; rxNum<=STOP_RX; rxNum++)
                for (rate=0; rate<4; rate++)
                    if (rxUsed[rxNum][rate])  //if all receiver in all rates are not used then break
                        brk=0;                 //this receive is used so no break statement
*/
        }
        else {
            brk=1;   //break
        }
        if (brk)  //if receiver not used continue in loop
            break;
    }

    saveResults();
```

```
// printf("Complete Ber Result\n");
// getch();

   freeMemory();
}
/***********************************************
/* allocateAndInitVars
/*
/* Purpose: Allocate memory and initialize global variable results
/***********************************************/
void allocateAndInitVars(void)
{
   printf("Allocating memory\n");
   for (int frame=START_FRAME;frame<=STOP_FRAME;frame++) {
      pFlexCycle[frame] = new (flexBlock);
   }

   printf("Initilize variables\n");
   for (int rxNum=START_RX;rxNum<=STOP_RX;rxNum++) {
      for (int rate=0;rate<4;rate++) {
         for (int dbm=START_DBM;dbm<=STOP_DBM;dbm++) {
            results[rxNum][rate][dbm].usableCodewordBits[0] = 0.0;
            results[rxNum][rate][dbm].usableCodewordBits[1] = 0.0;
            results[rxNum][rate][dbm].codewordErasures[0] = 0.0;
            results[rxNum][rate][dbm].codewordErasures[1] = 0.0;
            results[rxNum][rate][dbm].frameErasures[0] = 0.0;
            results[rxNum][rate][dbm].frameErasures[1] = 0.0;
            results[rxNum][rate][dbm].frameErasures[2] = 0.0;
         }
         rxUsed[rxNum][rate] = 1;  //assume all used
      }
   }
}

/***********************************************
/* freeMemory
/*
/* Purpose: Free all allocated memory variables
/***********************************************/
void freeMemory(void)
{
// printf("Destroying memory\n");
   for (int frame=START_FRAME;frame<=STOP_FRAME;frame++) {
      delete (pFlexCycle[frame]);
   }
}
```

9. Vita

Scott Lindsey McCulley

Scott Lindsey McCulley was born on August 26, 1969, in Wilmington, Delaware. He grew up in the area and graduated from Salesianum High School in 1988. Scott obtained a Bachelor of Science in Electrical Engineering with a Math Minor from Virginia Polytechnic Institute and State University in 1992. He graduated with Honors and Magna Cum Laude. Scott went on to pursue a master degree in the same field and complete all course work by 1993. In the summer of 1993, he went to work as the Director of Engineering for TSR Technologies, a company that Dr. T.S. Rappaport founded. In the fall of 1993, TSR Technologies was sold to Grayson Wireless, formerly Grayson Electronics. Scott is currently working for Grayson Wireless, the sponsor of this research, as a Product Development Engineer. He has helped design and implement numerous measurement and test equipment and software for the wireless industry, including paging, cellular, and PCS.