# Communications Research Centre

## DIVERSITY PERFORMANCE IN FREQUENCY-HOPPED 8-ARY SIGNALS-IMPLEMENTATION AND MEASUREMENTS

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*P. Tardif and E.B. Felstead*
*(Communications Technologies Research Branch)*

**CRC REPORT NO. 1432**

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**Ottawa**

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## ABSTRACT

A micro-processor based signal processor was built and tested that is capable of performing the diversity combining needed to reduce the error rate of 8-ary non-coherent FSK signals demodulated onboard a satellite. Two combining techniques were implemented and tested: hard decision majority vote (HDMV) and normalized envelope detection (NED). Measurements of bit error rate performance of these two techniques in the presence of system noise plus either partial-band noise (PBN) or multiple tone (MT) jamming were made for levels of diversity, L, from 1 to 32. The signal-to-jammer ratio (SJR) levels used were so low that worst-case jamming was always with the full band jammed. Results showed that HDMV combining could give error correction for PBN jamming for a SJR as low as 0 dB but gave no correction for MT jamming when the SJR was less than 10 dB even for L as high as 32. NED combining handled PBN jamming better than the HDMV and performed very well against MT jamming even at a SJR as low as 0 dB. Results show for the low SJR regime considered, that NED combining is clearly the error correction method of choice over HDMV combining and even over low-rate convolutional coding.

## RÉSUMÉ

Un processeur pour le traitement de signaux a été développé en laboratoire afin d'exécuter la combinaison en diversité requise à bord du satellite pour réduire le taux d'erreur d'un signal modulé par déplacement de fréquence non-cohérente (FSK) à huit niveaux. Deux techniques de diversité furent implantées et vérifiées: détermination de la majorité par décision ferme (DMDF) et la détection normalisée de l'enveloppe (DNE). Ces deux techniques ont été évaluées en présence d'un bruit de fond et d'un brouillage intentionnel soit par du bruit sur une partie de la bande passante (BPB) ou soit par tonalités multiples (TM). Des mesures sur les performances des taux d'erreurs ont été faites pour des niveaux de diversité L variant de 1 à 32. Les rapports signal à brouillage intentionnel RSBi utilisés étaient si faibles que le brouillage complet de la bande (cas extrême) était employé. Les résultats ont démontré que la technique DMDF peut fournir une correction d'erreur avec un RSBi aussi faible que 0 dB avec du brouillage de type bruit mais n'offre aucune correction avec un RSBi inférieur à 10 dB lorsque des tonalités sont utilisés comme méthode de brouillage et ce, même pour un niveau de diversité L aussi grand que 32. La méthode de l'enveloppe normalisée, par contre, résiste beaucoup mieux au BPB que la DMDF. Ses performances avec du brouillage par tonalités sont aussi supérieures même à des RSBi aussi faible que 0 dB. Les résultats prouvent, en dépit du faible RSBi étudié, que la DNE est sans aucun doute la méthode de correction d'erreurs de premier choix sur la DMDF et même, demeure la technique préférée sur le codage récurrent à faible rendement.

## EXECUTIVE SUMMARY

Future military communications satellites will likely use onboard processing to protect against uplink jamming. A very powerful anti-jam technique is frequency hopping (FH) spread-spectrum. However, this technique has limitations against very powerful and intelligent jammers. The performance of FH systems against such jammers can be improved through the use of a redundancy method called diversity,.wherein data symbols are repeated L times during transmission, and at the receiver special methods of diversity combining of these repeated symbols are used. Practical implementation of such diversity combining onboard a satellite payload requires that maximum use be made of processing already in place, that multiple simultaneous users be supported, and that any extra processing be compatible with payload constraints on weight and power.

In this report, a laboratory system is developed that performs diversity combining in real time using a common micro-processor chip. An existing surface-acoustic wave processor served as the preprocessor that would be used in an actual payload. Two forms of diversity combining, hard-decision majority-vote (HDMV), and normalized envelope detection (NED), were implemented. Bit-error rate performance against high levels of worst-case forms of jamming was measured

The work demonstrated that both HDMV and NED diversity combining were easily implemented for real time operation and should be able to be implemented on an actual payload. The measurements of performance showed that both diversity combining methods, and especially the NED method, greatly reduced the effects of powerful and intelligent jamming.

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# 1. INTRODUCTION

Frequency-hopping (FH) spread-spectrum (SS) techniques are useful for combatting jamming in military radio communication systems. These systems typically use M-ary frequency-shift keying (FSK) modulation and, for practical reasons, tend to be noncoherent from hop to hop. The hop rate, $R_h$, should be high enough that follower jammers are not a threat. In milsatcom systems of current interest, it is useful to transmit a single M-ary symbol on L separate hops. The use of one or more hops per transmitted symbol is referred to as fast frequency hopping in the relative sense and is a form of time diversity. The number of hops, L, per symbol is called the order or level of diversity. This redundancy can be used as an extra form of processing gain in addition to that obtained from the FH SS.

Often, standard error correction (EC) coding uses some of the available redundancy to overcome the effects of partial-band noise (PBN) jamming or multitone (MT) jamming wherein some hops are jammed and others are not. However, when the average jamming power is sufficiently large, the worst-case jamming strategy is to spread the jamming power throughout the band so that every hop is jammed. Then, standard EC coding techniques are insufficient on their own. Diversity combining techniques can be applied to reduce the error rate caused by such a severe jammer.

Numerous diversity combining techniques have been suggested in the literature. Only two methods are considered in this report namely hard-decision majority-vote (HDMV) combining [1], and normalized-envelope detection (NED) combining [2]. The HDMV method is selected because of its ease of implementation and versatility. The NED combining was chosen because of its potential for very good performance combined with relative ease of implementation.

An experimental system was built that permitted measurement of the bit-error rate (BER) of FH 8-ary FSK signals in the presence of system noise plus full-band noise jamming or full-band MT jamming. Both HDMV and

NED combining were implemented for values of L from 1 to 32. A rate 1/2 convolutional codec was also tested in the system for purposes of comparison.

In this report, the experimental system is described. Then results of BER measurements are given for both HDMV and NED combining in the presence of very strong noise and tone jamming. The measured result for HDMV and NED combining are compared to theoretical results obtained using a low-rate convolutional EC code.

## 2. GENERAL SYSTEM DESCRIPTION

### 2.1 Transmitter Structure

The basic elements of a typical M-ary noncoherent FSK (NCFSK) FH transmitter are shown in Fig. 2.1. The input binary data have a period $T_b$ s and a rate $R_b$ bits/s. The data may be convolutionally EC encoded at a rate r= (number of bits in)/(number of encoded bits out) so that the encoded period is $T_c = rT_b$ s and the encoded bit rate is $R_c = R_b/r$ bits/s. This binary information is converted $k = \log_2 M$ bits at a time into one symbol tone of frequency $f_l$ where $f_l$ has one of M possible values. An FSK channel contains M frequency bins. The symbol duration is $T_s = kT_c$ s, and the symbol rate is $R_s = R_c/k$ symbols/s. Finally, the symbols are mixed with a frequency-hopping tone of frequency $f_h$ and duration $T_h$ and hop-rate $R_h$. For fast FH, L>1, where L is an integer number of hops/symbol. The input and output periods and rates are related, respectively, by $T_h = rk\, T_b/L$ and $R_h = LR_b/(kr)$.

### 2.2. Receiver Structure

A typical receiver is shown in Fig. 2.2. The input of the receiver is the vector sum of the signal, jamming, and system thermal noise. The signal tone received has the form

$$\sqrt{2a}\, \cos\, [2\pi(f_h + f_l)t + \phi] \qquad (1)$$

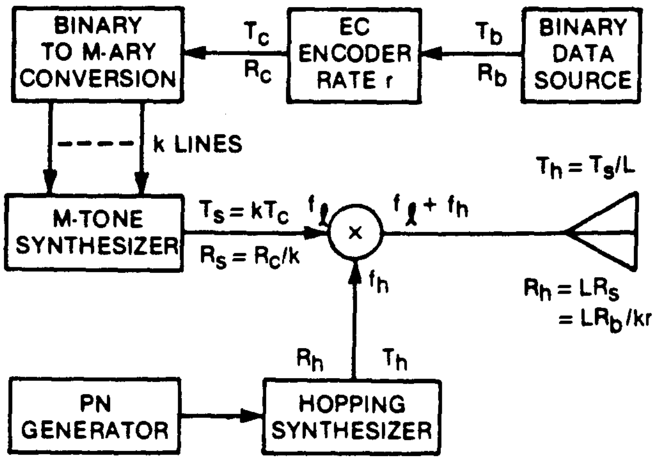


Fig. 2.1. Block diagram for a fast hopped M-ary NCFSK transmitter.

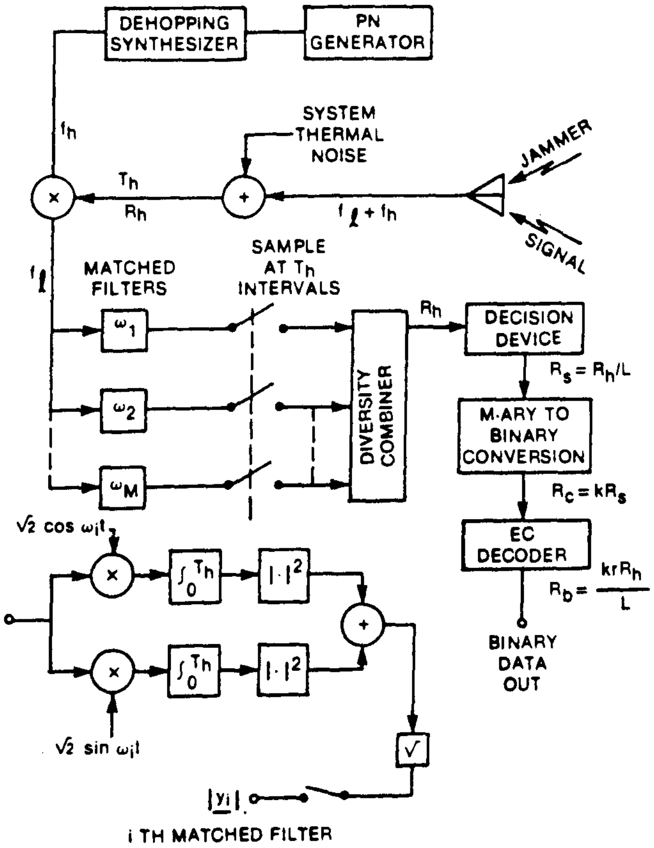


Fig. 2.2. Block diagram for a fast hopped M-ary NCFSK receiver.

for a period of $T_h$ where $\sqrt{2a}$ is the amplitude and ø is the phase. Its rms power is $a^2$. The signal energy on a single hop is $E_h = a^2T_h$. The dehopped signal of frequency $f_l$ is fed to a bank of M bandpass filters for demodulation and a decision is made to estimate which of the M tones has been transmitted (i.e. symbols). That decision is based on L hops received. The diversity combiner and the decision device will be the main subject of this report. Once the symbol transmitted has been estimated, it is then converted into its binary form and decoded to restore the original information rate $R_b = krR_h/L$.

## 2.3 BER Performance Region

One of many ways to describe the bit-error-rate (BER) performance is shown in Fig. 2.3 from [1] for typical parameters for PBN jamming with and without system noise. The probability of bit error, $P_b$, at the output of the 8-ary NCFSK detector is plotted as a fraction, $\gamma$, of the bins jammed for various values of the received signal-to-jammer ratio. SJR is defined as the signal power received divided by the average jammer power if it were spread uniformly across the hop band. As the jamming level is increased, the peaks flatten out and eventually the worst case jamming occurs at $\gamma$=1. It is seen that for SJR less than about 10 dB, the values of $P_b$ tend to be above 0.1 and can approach 0.5. Similar curves result for MT jamming. Fig. 2.3 gives the theoretical probability of a bit error which is to be distinguished from the bit-error rate (BER) which is a value measured on an actual system. Therefore, in this report all measured results are in terms of BER.

If the BER into a standard rate-1/2 EC decoder is high, say >0.1, the decoder tends to fail in the sense that the output BER is higher than the input BER. Under this circumstance, the use of EC coding makes the final BER worse than if it had not been used at all. In this report, the purpose of the diversity combiner is to reduce the BER to below 0.1 so that the subsequent EC decoder can reduce the output BER to below the objective of $10^{-5}$. In all measurements, it is assumed that the SJR is sufficiently poor that worst case jamming occurs for $\gamma$=1 and, therefore, every hop is jammed.

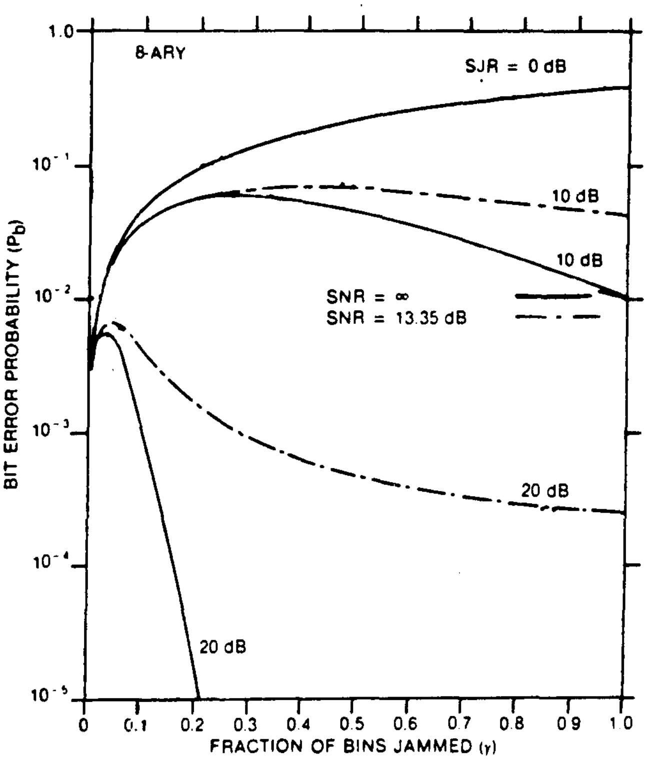


Fig. 2.3. $P_b$ as a function of $\gamma$ for 8-ary NCFSK in the presence of PBN jamming with and without system noise where SNR = 13.35 dB.

## 2.4 Hard Decision Majority Vote (HDMV) Combining

For HDMV combining, a hard decision on which of M tones is received is made on each hop and then the tone with the most counts or "votes" in L hops is declared the symbol received. On the left side of Fig. 2.4 is an example of how HDMV operates. Here, L=5, M=8, and there is a single jamming tone per channel (worst case in Houston's sense [1]). Because the largest tone on each hop is given a weighting of 1, the jammer bin is always selected. For this example, the seventh bin gets 2 hits and is erroneously selected. Obviously, for the jammer tone larger than the signal tone, as in this example, a BER of 0.5 would always result regardless of the value of L.

The probability of symbol error, $P_{SV}$, out of the HDMV combiner is a function of the probability of symbol error, $P_{SD}$, out of the demodulator and has the general form

$$P_{SV} = \sum_{i=L/2}^{L} a_{MLi} P_{SD}^{i} (1-P_{SD})^{L-i} \tag{2}$$

where the coefficients $a_{MLi}$ are tabulated as functions of M and L in [1] for L = 3 to 9 and some values of M. Also, some example calculations are given in [1].

## 2.5 Normalized Envelope Detection (NED) Combining

In this method, the amplitude envelopes, $a_i$, i=1 to M, in each bin are normalized by the total amplitude received in all hops to give

$$y_i = a_i / \sum_{j=1}^{M} a_j \tag{3}$$

The $y_i$'s are summed over the L hops and the largest of the M sums is declared to be the tone received.

On the right side of Fig. 2.4 is an example of how NED combining operates. The signal and jamming tones received are identical to those for the HDMV example. However, for the NED combining, the figure. shows the amplitudes after normalizing. The sum of these 5 normalized amplitudes gives the correct bin with the largest sum and, therefore, a correct decision is made. Thus, NED combining can still operate well even when every hop is jammed at levels larger than the signal itself. The normalization prevents a strong jammer on one hop having undue influence on the final decision.

Gong [2] simulated the NED approach and showed that processing gain can be improved using this technique. This method is more complex to implement than HDMV because of its normalization aspect but its extra processing gain as demonstrated later makes it a promising technique.

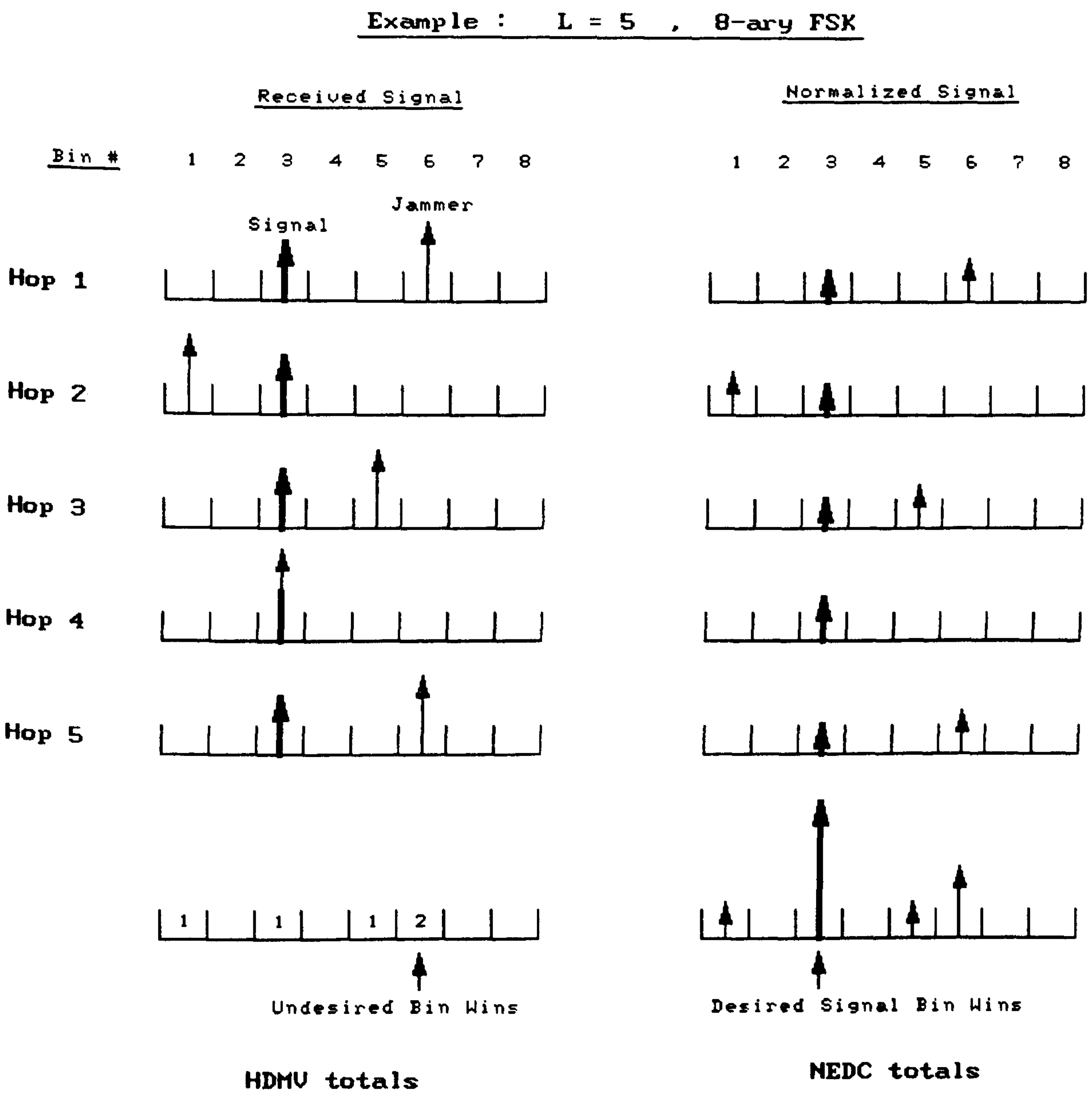


Fig. 2.4. Illustration of HDMV and NED combining techniques.

## 3. IMPLEMENTATION

A simplified block diagram of the complete measurement system is shown in Fig. 3.1. It is divided into three sections representing three components of a communication system which are: the earth terminal transmitter (on the top), the channel (in the middle), and the receiver (bottom). Table 3.1 summarizes the main characteristics of the transmitter and receiver. These components are described in the following subsections and certain diagrams are provided in Appendix A.

Table 3.1.

Some parameters of the Measurement System

| TRANSMITTER | |
|---|---|
| Data rate if coding not used | 1875 b/s |
| Data rate if coding used | 937.5 b/s |
| Rate at input to converter | 1875 b/s |
| 8-ary symbol rate | 625 sym/s |
| Repetitions, L, of each symbol | 32 |
| Simulated hop rate | 20 k hop/s |
| IF frequency | 70 MHz |
| Tone spacing | 200 kHz |

| RECEIVER | |
|---|---|
| IF frequency: | 70 MHz |
| Carrier input level: | -20 dBm into 50 ohms |
| SAW transform rate: | 20 k transforms/s |
| A/D sampling rate: | 1.6 MHz |
| Level of diversity: | 1-32 (jumper selectable) |
| Combining: | HDMV/NED (jumper selectable) |
| Decoding rate: | 1/2, hard decision (optional) |
| Decoded bit rate if EC used | 937.5 |
| Bit rate if EC not used | 1875 b/s |

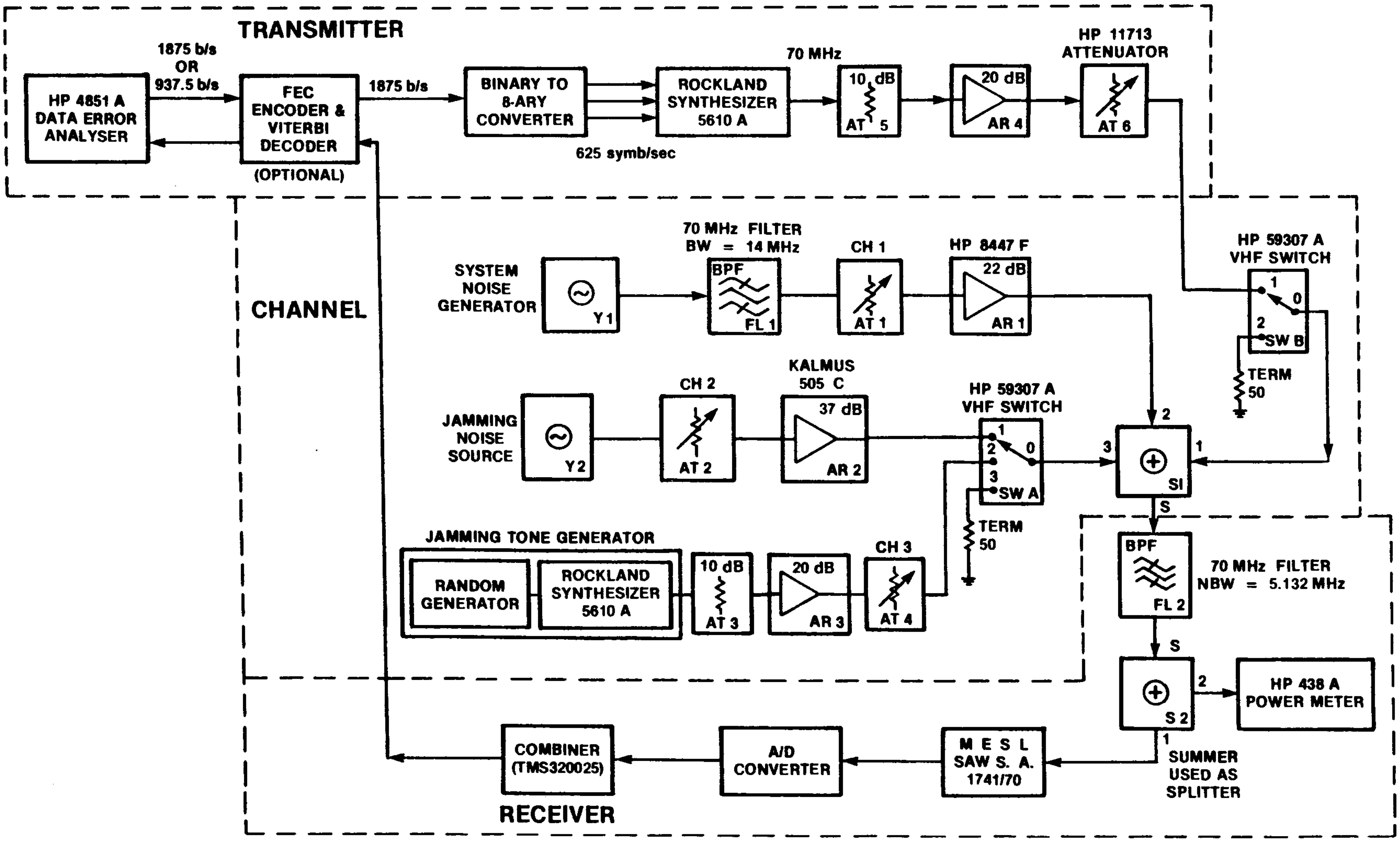


Fig. 3.1. A block diagram of the experimental measurement system.

It was desired to simulate the effects of frequency hopping without going to the expense of actually hopping and dehopping. To this end, it was only necessary to ensure that the input to the receiver, which corresponds to the dehopped signal, was phase incoherent from "hop" to "hop". The phase discontinuity is easily achieved by triggering the FSK symbol-generating frequency synthesizer for every equivalent hop period thereby dividing each symbol period into L-phase-discontinuous equivalent hop periods.

### 3.1 Transmitter

For the transmitter section, binary data are generated at 1875 b/s if no subsequent EC coding is used, and at 937.5 b/s if EC coding is used. The codec card contains a convolutional, constraint length 7, rate r=1/2 encoder and a Viterbi decoder which can be disabled from the jumpers located on the board. Thus, a rate of 1875 b/s is always used at the input to the binary-to-8-ary converter, which is located on the same board as the codec. The output of the converter is at a rate of 625 sym/s. These symbols are used to drive the Rockland frequency synthesizer to generate one of eight frequencies. The frequency bin spacing is 200 kHz so that the channel width is 1.6 MHz. The input to the synthesizer is strobed at 20 kHz so that for each input symbol, there are 32 output tone bursts of a given frequency but phase discontinuous. Thus, the simulated hop rate is 20 k hop/s and the available diversity is L=32.

### 3.2 Channel

The purpose of the "channel" is to add system noise and jamming to the 8-ary NCFSK signal. As seen in Fig. 3.1, the signal, system noise source, and both types of jamming sources have variable attenuators to aid in setting desired values of SNR and SJR. For MT jamming that is worst case in Houston's sense, on the jammed hops there is only one jamming tone in the 8-bin signal channel. The particular bin occupied varies hop to hop. Therefore, a single jamming tone was generated to fall at random in one of the 8 bins. Thus, the location of the jamming tone in the 8-bin channel changes randomly hop to hop, and properly simulates an MT jammer. The circuit for implementing this random frequency change is shown in Fig.A.3.

## 3.3 Receiver

The demodulation of the NCFSK signal is done by means of taking the Fourier transform which is implemented by a SAW-based chirp transformer. The transformer was made by Racal-MESL in Scotland and its performance is described in [3]. This transformer has a 0.25 dB bandwidth of 4 MHz centered on 70 MHz. Its integration time for the Fourier transform is 25 μs and has a 50% duty cycle. The 20 k hop/s hop rate implies a hop interval of 50 μs of which only 25 μs is processed so that the effective hop period, $T_h$, is 25 μs. The SAW processor has an adjustable window shape which for these experiments was set so as to provide a window similar to the Kaiser-Bessel (see Fig. 3.5 in [3]). The combination of window loss plus implementation loss was measured in [3] to be 1.8 dB and is accounted for in a manner described in Sec. 3.5.

The centres of the M=8 frequency bins were spaced at 200 kHz. For this chirp transformer, the scale factor of the transform is 0.16 MHz/μs so that 200 kHz is represented by 1.25 μs. The output is sampled every 0.625 μs but only the eight samples taken from the centers of the 8 frequency bins were processed. These samples were then A/D converted and sent to the diversity combiner which performed either the HDMV or NED combining of L hops. The resulting 8-ary symbol decision is converted to binary. These bits are returned to the data error analyzer which measures the BER. Optionally, the combiner output bits can be hard-decision Viterbi decoded by enabling the EC decoder.

## 3.4 Comments on Circuits

In order to minimize engineering effort, some of the hardware used in [3] was re-utilized for the tests: the timing card #1, A/D converter card and the MESL spectrum analyzer. Those were designed to accommodate M-ary

NCFSK, hop rate = 20 k hop/s. Two new cards had to be designed: the codec board and the processor board.

The codec board also contains the binary to 8-ary converter, timing for the data error analyzer and interface drives for the Rockland synthesizer FSK modulator.

The processing board is TMS 320 based. It accepts data from the A/D converter and performs the HDMV and NED combining techniques described before. L is jumper selectable. Recall that every symbol is transmitted 32 times. Only L of these are used for the combining process so that 32-L hops are not used. Although wasteful, this approach made the measurement system easier to implement for a variable L. Flow charts are provided in Figs. 3.2 and 3.3.

## 3.5 Definition and Measurement of SNR and SJR

### 3.5.1 System Noise, SNR

A signal-to-noise ratio of SNR=13.35 dB was used in all the measurements. This baseline results in a BER = $10^{-5}$ for binary NCFSK in the absence of jamming. The SNR is defined as

$$SNR = \frac{a^2}{2\sigma_n^2} \tag{4}$$

where $a^2$=C is the power of the received carrier and $\sigma_n^2$ is the single component variance of the complex noise in one bin. The familiar form is simply

$$SNR = \frac{E_h}{N_o} = \frac{CT_h}{N/B} \tag{5}$$

where $E_h=CT_h$ is the received energy per hop, $N_o$ is the one-sided noise power spectral density, and $T_h$ is the hop duration. The value of $N_o$ is calculated from N/B where B is the noise equivalent bandwidth of the filter shown in the channel section of Fig. 3.1 and N is the noise power at the filter output. Both C and N are measured in watts with a power meter.

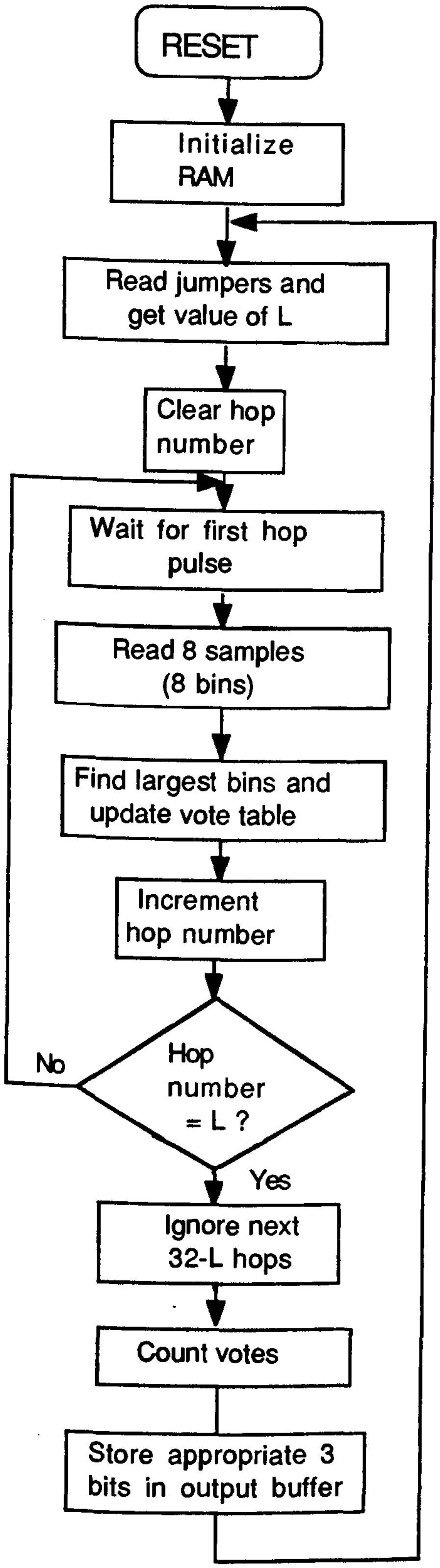


Fig. 3.2. HDMV simplified flowchart.

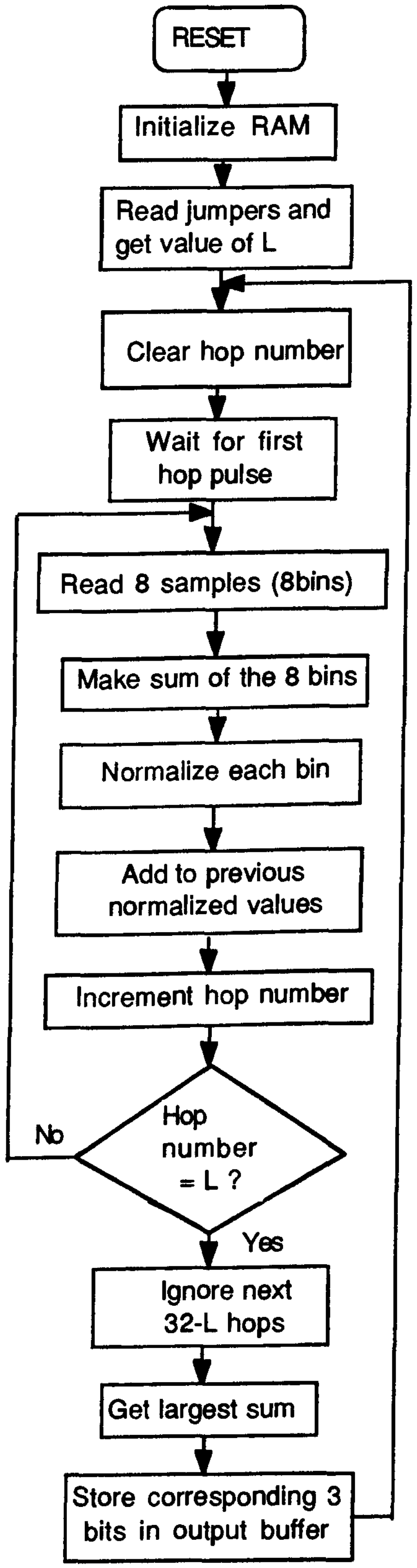


Fig. 3.3. NED simplified flowchart.

The effective hop period, as noted above, was $T_h$=25μs and the filter bandwidth was B=5.132 MHz. Therefore, (5) becomes SNR=128.3 C/N which in dB is

$$SNR_{dB} = C_{dB} - N_{dB} + 21.08.$$

As noted earlier, the SAW processor has a combined window and implementation loss of 1.8 dB. Therefore, the effective SNR is calculated from

$$SNR_{dB|eff} = C_{dB} - N_{dB} + 19.28. \quad (6)$$

This is the SNR that would be required by an ideal processor with no window loss to achieve the same BER performance as the SAW processor. In the measurements, C was usually held constant while N was varied and measured on the power meter to correspond to a desired SNR.

3.5.2 PBN - SJR

For PBN jamming, the standard definition of effective SJR is

$$SJR_{PBN} = E_h/J_o \quad (7)$$

where $J_o$ is the power spectral density that would result if the total noise jamming power were spread uniformly across the hop band. In PBN jamming, a fraction, γ, of the band is jammed with a power density of $J_o/\gamma$ W/Hz and the remaining fraction, 1-γ, is not jammed.

In order to simulate PBN jamming without actually hopping, it is only necessary to switch on the noise jammer source on γ of the hops with a power density of $J_o/\gamma$. The value of $J_o/\gamma$ is simply $J_{PBN}/B$ where $J_{PBN}$ in watts is the power measured through the filter of width B. For the measurement of $J_{PBN}$, the jamming noise is turned on continuously and all other sources are turned off. Thus, (7) becomes, in terms of measured quantities,

$$SJR_{PBN} = \frac{CT_h}{\gamma J_{PBN}/B} \quad (8)$$

As discussed earlier, only values of $\gamma=1$ are considered here, i.e., all hops are jammed. With the same values of $T_h$ and B as before, and with compensation for the 1.8dB combined window and implementation loss, the effective SJR is

$$SJR_{PBN|eff\,dB} = C_{dB} - J_{PBNdB} + 19.28\ dB. \tag{9}$$

Again, during the measurements, C was held constant and $J_{PBN}$ was varied.

3.5.3. MT - SJR

For MT jamming, a fraction of $\gamma$ of the bins are jammed with a power of $J/\gamma$ and the remaining fraction, $1 - \gamma$, have no jamming. The usual definition of SJR is

$$SJR_{MT} = \frac{C}{\gamma(J/\gamma)} = \frac{C}{J}. \tag{10}$$

Here, only the worst case MT jamming in Houston's sense was considered so that on jammed hops there is only one jamming tone in the M-bin channel. Therefore, the fraction of hops jammed is $\beta = \gamma M$. Since for this work every hop is jammed, then $\beta = 1$ and $\gamma = 1/8$.

The power, $J_{MT}$, of the single jamming tone is measured at the output of the filter with the tone generator turned on continuously and all other sources turned off. Since $J_{MT}$ is $J/\gamma$, then (10) becomes

$$SJR_{MT} = \frac{8C}{J_{MT}} \tag{11}$$

which in dB is

$$SJR_{MT|dB} = C_{dB} - J_{MTdB} + 9.03\ dB. \tag{12}$$

Again, during measurements of SJR, C was held constant while $J_{MT}$ was varied.

## 4.0 MEASUREMENTS

### 4.1 Measurements with System Noise Only

The first performance tests made were measurements of bit-error rate (BER) as a function of system noise with no diversity (L=1). The measurement system shown in Fig. 3.1 was used with system noise as the only interference. The BER was measured as a function of SNR as calculated from (6). These measurements were done first without EC coding and then with coding. A rate r = 1/2, constraint-length 7 convolutional EC code was used with Viterbi decoding. Only the hard-decision mode was used for better comparison to the subsequent measurements wherein jamming is used. (The soft-decision mode should not be used with jamming.)

The results of the SNR measurements are shown in Fig. 4.1. The theoretical probability of bit error, $P_b$, for M = 8 was calculated from

$$P_b = \frac{\exp(-E_h/N_o)}{14} \sum_{j=2}^{8} (-1)^j \frac{8!}{(8-j)!\, j!} \exp(E_h/jN_o) \quad (13)$$

The fact that without the codec, the measured results came very close to the theoretical performance, demonstrates that the implementation loss of 1.8 dB incorporated into the SNR definition (6) was indeed a good value. At the lower values of BER, the codec showed a gain over the non coded curve of about 2.75 dB. This value compares well with the 3.0 dB gain expected from theory.

### 4.2 Measurement Results for PBN Jamming

In the second set of measurements, partial-band noise (PBN) jamming was added to the system shown in Fig. 3.1. All hops were jammed with additive white Gaussian noise (AWGN) at a $SJR_{PBN}$ level as determined by (9). A background system noise was always added at a level of SNR = 13.35 dB. Both HDMV and NED combining were used. The codec was not used in these measurements.

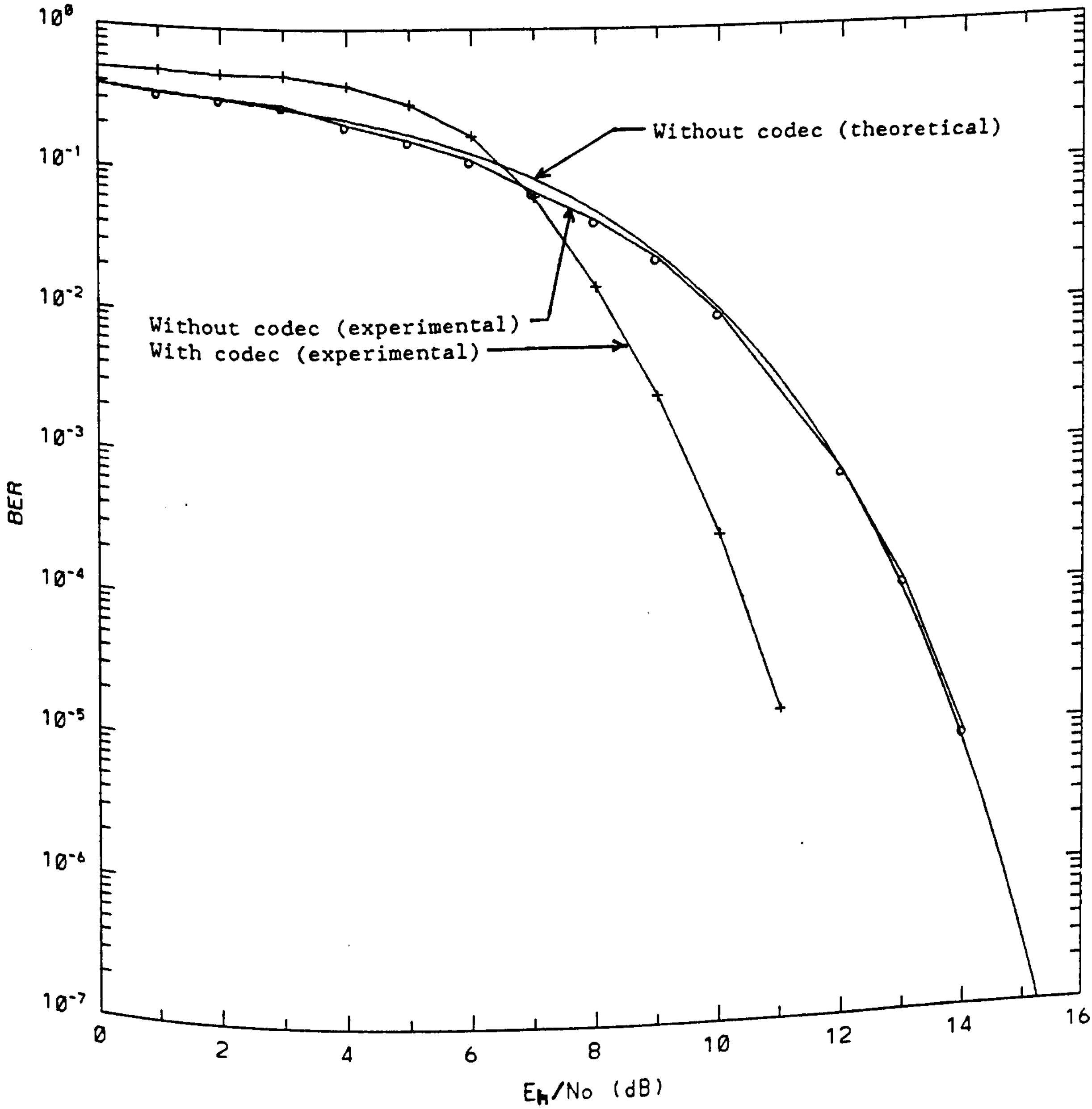


Fig. 4.1. BER performances of 8-ARY NCFSK in the presence of system noise with and without use of the codec.

The BER performance as a function of diversity, L, for the two combining techniques is shown in Fig. 4.2 for values of SJR = 0, 5, and 10 dB. The BER value for L=1 is also the baseline error rate before any diversity combining is done. As predicted in [1], the HDMV was found to give no improvement for L=2 over L=1.

The NED combining is seen to give superior BER performance to HDMV combining for all levels of diversity above L=1 and for all 3 values of SJR. An interesting general rule was discovered that to achieve a certain BER for a given SJR, the L required for the HDMV combining is always about 1.7 times higher than the L required for NED combining. For example, for $SJR_{PBN}$ = 5 dB, in order to achieve BER = $10^{-5}$, the HDMV requires L = 26.6 but the NED requires only L = 15.56, a ratio of 1.7. These non-integer values of L were obtained from the graph in Fig. 4.2 for the purpose of calculating the ratio. This reduction factor of 1.7 can be used by a NED system either to increase the date rate by 1.7, or to improve the BER performance substantially.

PBN jamming with $\gamma$=1 is merely continuous interference with AWGN. For this interference, it is meaningful to consider a processing gain of the diversity combining. The processing gain, $PG_D$, due to the diversity combining measurements is listed in Table 4.1. The values of $PG_D$ were determined as follows. First the values of BER with no diversity combining, i.e. L=1, were taken from Fig. 4.2. These values of BER were then used in Fig. 4.1 to determine the corresponding SNR = $E_h/N_o$. Then, for the selected value of L shown in Table 4.1, the corresponding BER thereby achieved is found from Fig. 4.2. Once again, Fig. 4.1 is used to determine the SNR required to achieve this value of BER. The difference in dB between the SNR required with no diversity and the SNR required with diversity is taken to be $PG_D$. For example, consider HDMV with $SJR_{PBN}$ = 5dB. At L=1 in Fig. 4.2, the BER = 0.2. This BER is found in Fig. 4.1 to require an SNR = 4.2 dB. The same procedure is repeated for a value of L ≠ 1, arbitrarily chosen here as 18. The matching SNR is 12.4 dB. The difference is 8.2 dB as listed in Table 4.1.

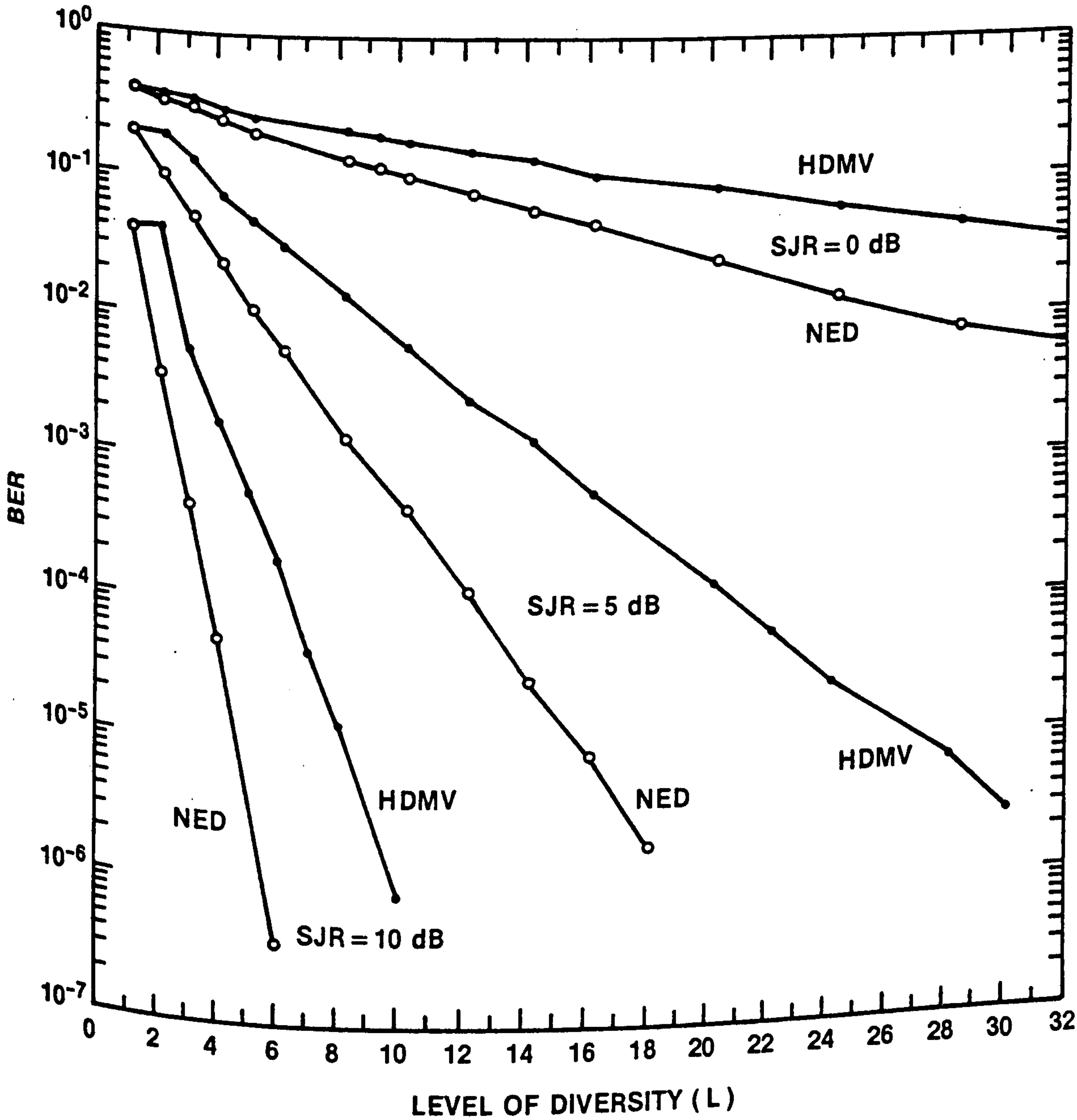


Fig. 4.2. BER performance in the presence of PBN jamming at 3 values of $SJR_{PBN|eff}$ plus system noise at $SNR|_{eff}$ = 13.35 dB.

Table 4.1

Processing Gain for $SJR_{PBN}$ = 0, 5, and 10 dB Using HDMV and NED Combining.

| $SJR_{PBN}$ dB | L | EXPERIMENTAL $PG_D$ dB | | COHERENT GAIN, $PG_C$ =10 log L dB |
|---|---|---|---|---|
| | | HDMV | NED | |
| 0 | 30 | 8.2 | 10.3 | 14.8 |
| 5 | 18 | 8.2 | 10.3 | 12.6 |
| 10 | 6 | 4.4 | 6.7 | 7.8 |

The $PG_D$ of NED varies between 2.1 dB and 2.3 dB above $PG_D$ for HDMV. Note that the "reduction factor" discussed above is 1.7 which in dB is 2.3 dB. It appears that the reduction factor and processing gain in the presence of AWGN are the same thing.

The maximum theoretically achievable processing gains for HDMV and NED are not known. In lieu of such values, it is useful to use as a benchmark the coherent processing gain, $PG_c$. This gain is what would be achieved if it were possible to integrate coherently over L hop periods with the FSK demodulator. In the presence of the full band ($\gamma$ = 1) AWGN jamming considered in this section, the coherent gain is simply 10 log L dB which is tabulated in Table 4.1 for comparison to $PG_D$. The $PG_D$ for NED combining is 4.5 dB below $PG_c$ at SJR = 0dB but is only 1.1 dB below $PG_c$ at SJR = 10 dB. It is conjectured that as SJR becomes very large, $PG_D$ approaches closely to $PG_c$. At low SJR, one might be tempted to get back the 4 dB of more possible by increasing the hop period to $LT_h$. This approach is inappropriate because a simple change in jamming strategy would negate the anticipated gain and could easily make overall performance worse.

## 4.3 Measurement Results for MT Jamming

In this set of measurements, multiple-tone (MT) jamming is used in the system shown in Fig. 3.1. All hops were jammed with a single jamming tone at a $SJR_{MT}$ level determined from (12). The location of the tone varies randomly among the 8 bins as discussed earlier. A background system noise was always added at a level of SNR = 13.35 dB. Both HDMV and NED combining were used. The codec was not used in these measurements.

The BER performance of the two combining techniques is shown in Fig. 4.3 for three values of SJR. The baseline BER with no diversity (L = 1) for the MT jamming is significantly higher than that for the PBN jamming shown in Fig. 4.2. In fact, for SJR = 0dB and 5dB, the BER for MT jamming is very close to the largest possible value of 0.5. These baseline results demonstrate the well known fact that tone jamming causes more degradation than does PBN jamming for a given SJR.

The HDMV combining at low SJR of 0 and 5 dB, gives no apparent decrease in BER below the baseline value at L=1 for values of L up to 32. However, at SJR = 10 dB, the HDMV combining gives substantial reduction in BER. These measurement results for HDMV are easily understood. At SJR = 0, the tone is 9.0 dB above the signal level so that it will cause most of the L decisions to be incorrect. Conversely, at SJR = 10dB, the signal is always 1.0 dB above the jamming tone so that 13.35 dB system noise is the primary source of error and is easily corrected by the HDMV. As was also observed for PBN jamming, the HDMV shows no improvement at L = 2 over the BER for L = 1 for MT jamming.

The NED combining shows a good decrease in BER even at SJR = 0 dB, and a dramatic drop for larger SJR. These results are not surprising since the NED combining was originally devised as a counter to MT jamming. If the performance for NED combining in Figs. 4.2 and 4.3 are compared, it is seen that for L greater than about 5, the performance is roughly equal. Thus, the NED combining renders the MT jamming to be no more effective than PBN jamming thereby denying the jammer any

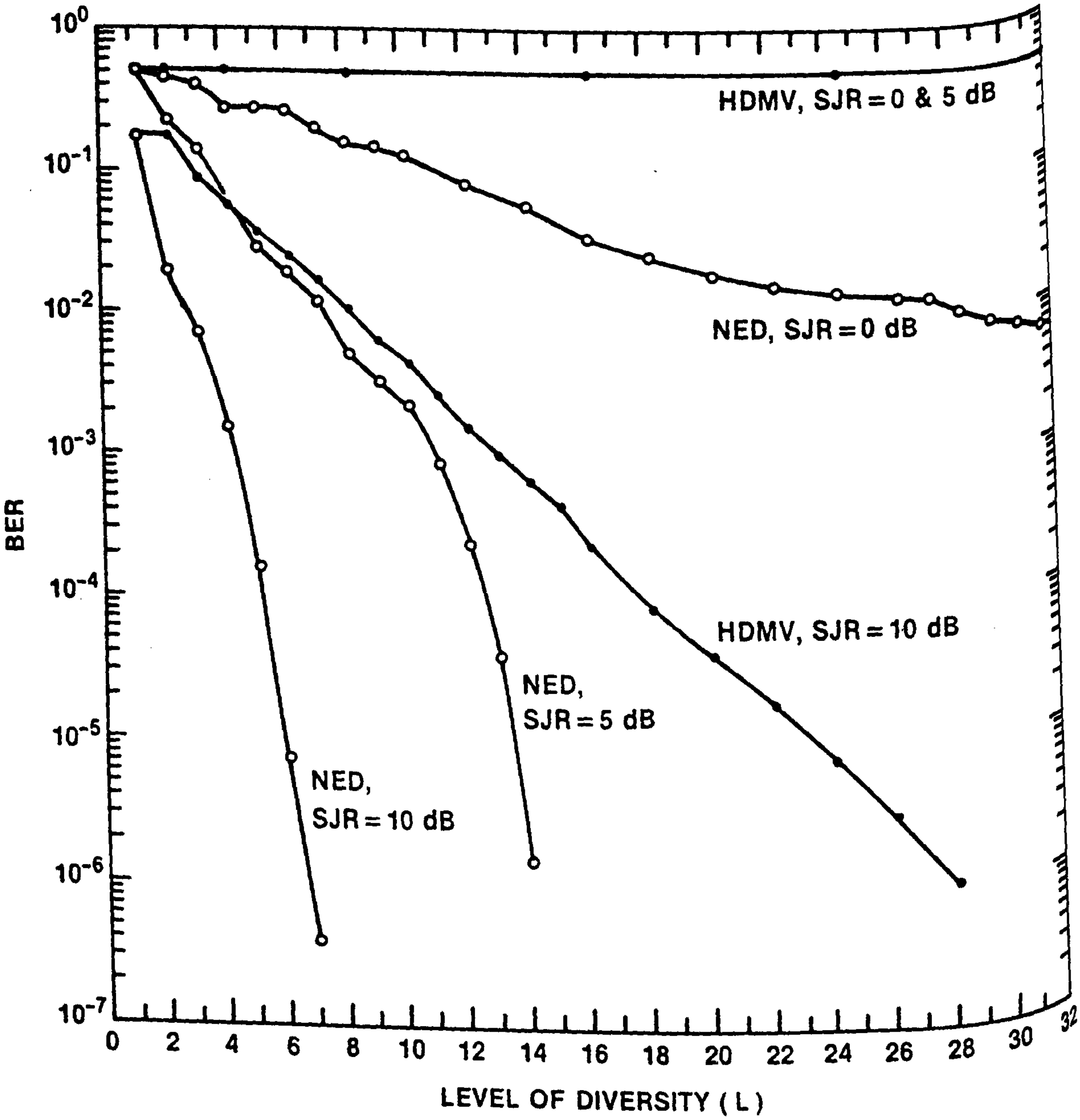


Fig. 4.3. BER performance in the presence of MT jamming at 3 values of $SJR_{MT}$ plus system noise at $SNR|_{eff}$ = 13.35 dB.

advantage to using tone jamming. To express it another way, the use of NED combining makes the overall performance almost independent of the type of jamming.

For a tone jammer, there is no increase in BER performance by increasing the coherent integration time because the integrated amplitude of both the signal and jamming tone are increased equally. Thus, for MT jamming there is no coherent processing gain to be obtained so that a comparison of diversity processing gain to coherent processing gain is not meaningful. Thus, it is warned that increasing the hop period by L times does not alter the BER whatsoever against MT jamming whereas using diversity L and the original hop period can improve the BER performance if HDMV combining is used, or greatly improve it if NED combining is used. Therefore, an attempt to achieve the large potential $PG_C$ against AWGN by increasing the hop period would be misguided because of the increased susceptibility to jamming by MT jammers.

## 5.0 EXTENSION OF MEASUREMENT RESULTS

In this section, the measurement results obtained in the previous section are used and combined in several ways. First, the coding and diversity results are combined to determine the combined performance. Then, the input BER as a function of output BER is found. Finally, comparison of diversity to low-rate codes is made.

### 5.1 Measurement Results for Concatenated Diversity Combining and Decoding

As discussed earlier, it is perhaps useful to concatenate a decoder with a diversity combiner so as to take advantage of the diversity combiner's robustness and versatility along with the data-rate efficiency of the coding. Therefore, in this section, the performance of diversity combining concatenated with decoding is compared to the performance of diversity combining alone. Rather than repeat measurements, the following results are based on combining the measured performance results for diversity from Figs. 4.2 and 4.3 with those for decoding from Fig. 4.1 in such a way as to predict the concatenated performance. Recall that a rate r=1/2 convolutional code of constraint length 7 was used along with hard-decision Viterbi coding.

In order to compare the performance with and without EC coding, it was decided to calculate the total redundancy, which is the product 2 L if coding is used or just L if not used, to achieve an output BER$\leq 10^{-5}$.

In Tables 5.1 and 5.2 is summarized the diversity, L, to achieve an output BER $\leq 10^{-5}$ with and without a concatenated codec. The total redundancy is then 2L in the columns "with coding" and L in the columns "without coding". Table 5.1 is for PBN jamming and Table 5.2 for MT jamming. For some of the values, a BER $\leq 10^{-5}$ could not be achieved for our maximum L of 32. These values are indicated by ">32".

For HDMV combining, it is seen that the level of diversity without coding is slightly more than double that with coding for PBN jamming and exactly double for MT jamming. Therefore, for HDMV combining, doubling the diversity, L, has approximately the same effect as adding the r=1/2 coding.

For NED combining, it is seen that for PBN jamming, the level of diversity without coding is no more than twice that with coding. For MT jamming, the diversity without coding is only about 50% higher than that required with coding. Therefore, for NED combining, it is more efficient with respect to data rate to use diversity alone rather than concatenated with a rate r=1/2 code.

These results arise from two characteristics of the coding considered. Firstly, this coding is best suited to AWGN interference. Clearly MT jamming does not even resemble AWGN and therefore, in terms of the redundancy required, NED combining alone far outperforms concatenating with a codec and even HDMV performs equally well with or without the codec. Secondly, as can be seen from Fig. 4.1, the input BER to this type of

Table 5.1

Levels of diversity (L) required to achieve a $BER<10^{-5}$ with PBN jammers, with and without rate r=1/2 hard-decision EC coding.

| SJR PBN (dB) | Level of diversity (L) | | | |
|---|---|---|---|---|
| | HDMV | | NED | |
| | WITHOUT CODING | WITH CODING | WITHOUT CODING | WITH CODING |
| 0 | >32 | >32 | >32 | >32 |
| 5 | 27 | 16 | 16 | 8 |
| 10 | 9 | 4 | 5 | 3 |

Table 5.2

Levels of diversity (L) required to achieve a $BER<10^{-5}$ with MT jammers, with and without rate r=1/2 hard-decision EC coding.

| SJR PBN (dB) | Level of diversity (L) | | | |
|---|---|---|---|---|
| | HDMV | | NED | |
| | WITHOUT CODING | WITH CODING | WITHOUT CODING | WITH CODING |
| 0 | >32 | >32 | >32 | >32 |
| 5 | >32 | >32 | 14 | 10 |
| 10 | 24 | 12 | 8 | 4 |

decoder must be <0.1 for any coding gain to be obtained but should be $<10^{-4}$ for the full coding gain to be achieved. Put another way, there is no coding gain at the input BER = 0.1 (the break even point) and as BER decreases, the coding gain increases until it achieves the maximum of about 3 dB at about BER = $10^{-4}$. Thus, the coding is not working at its full potential. But in the measurements, it is the region of $BER>10^{-4}$ that is considered.

5.2 Input Versus Output Bit-Error Rate Characteristics

Another way to display results is to express the bit-error rate, $BER_{out}$, at the output as a function of the input bit-error rate, $BER_{in}$. In Figs. 5.1, 5.2 and 5.3 are shown $BER_{in}$ as a function of $BER_{out}$ for values of L= 1,2,4,8,16 and 32 for both HDMV and NED combining in the presence of both PBN and MT jamming. These curves are taken from Figs. 4.2 and 4.3 by the following steps. For a particular value of L, combining technique and jamming type, the corresponding BER in Figs. 4.2 or 4.3 is the $BER_{out}$. The corresponding $BER_{in}$ is found from the same curve but at L=1. The ($BER_{out}$, $BER_{in}$) point is then plotted in Fig. 5.1, 5.2 or 5.3 as appropriate. the L=1 curves are just a plot of $BER_{in}$ = $BER_{out}$. Recall that there is a background SNR = 13.35 dB present for all conditions.

The results for HDMV for both PBN and MT jamming are shown in Fig. 5.1. The points for PBN are marked by an "X". The solid lines are straight lines drawn between these points; the dashed lines are straight line extrapolations outside the measured point. The points found for MT jamming are marked by circles. There was an insufficient number of points to draw reliable lines between them. However, the few points available fell very close to the lines found for PBN jamming.

The results of NED combining in the presence of PBN noise jamming are shown in Fig. 5.2. Only 2 points were available for L=8 and 16. For L=32 only a single point was available from Fig. 4.2. However, a second approximate point was found by extrapolating the results in Fig. 4.2. In Fig. 5.2 the dashed lines again indicate extrapolations.

The results of NED combining in the presence of MT jamming are shown in Fig. 5.3. Unfortunately many of the points were located close to the $BER_{in}$ = 0.5 line. Only 2 points we found off this line, one after L=2 and the other for L=4. Another point for L=8 was approximated by extrapolating Fig. 4.3. Therefore, most of the lines for L = 2, 4, and 8 are shown as dashed i.e.extrapolated or interpolated by eye. The lines for L = 16 and 32 never depart significantly from the $BER_{in}$ = 0.5. line.

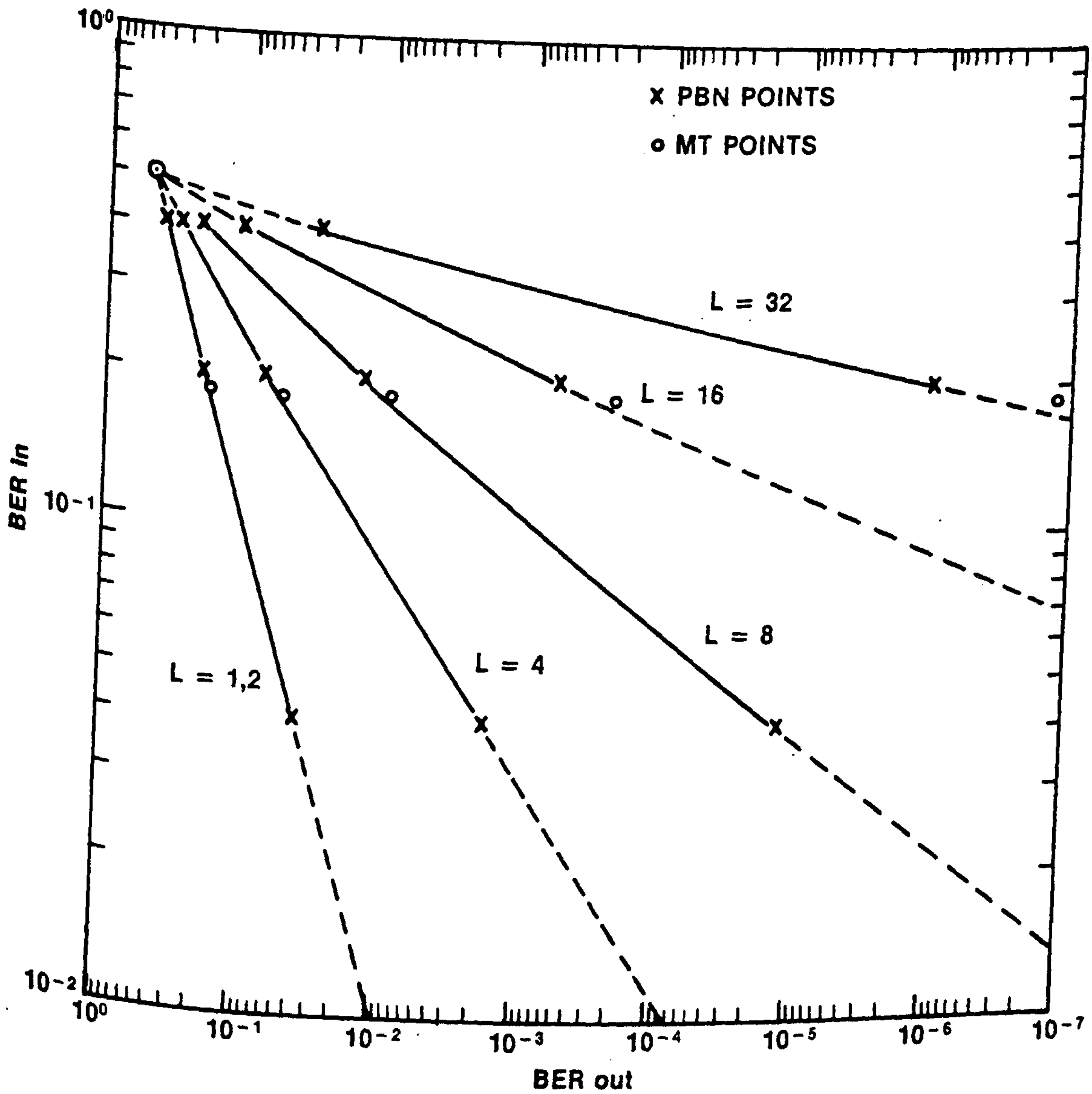


Fig. 5.1. $BER_{in}$ as a function of $BER_{out}$ for HDMV combining in the presence of PBN or MT jamming plus noise at $SNR|_{eff}$ = 13.35 dB.

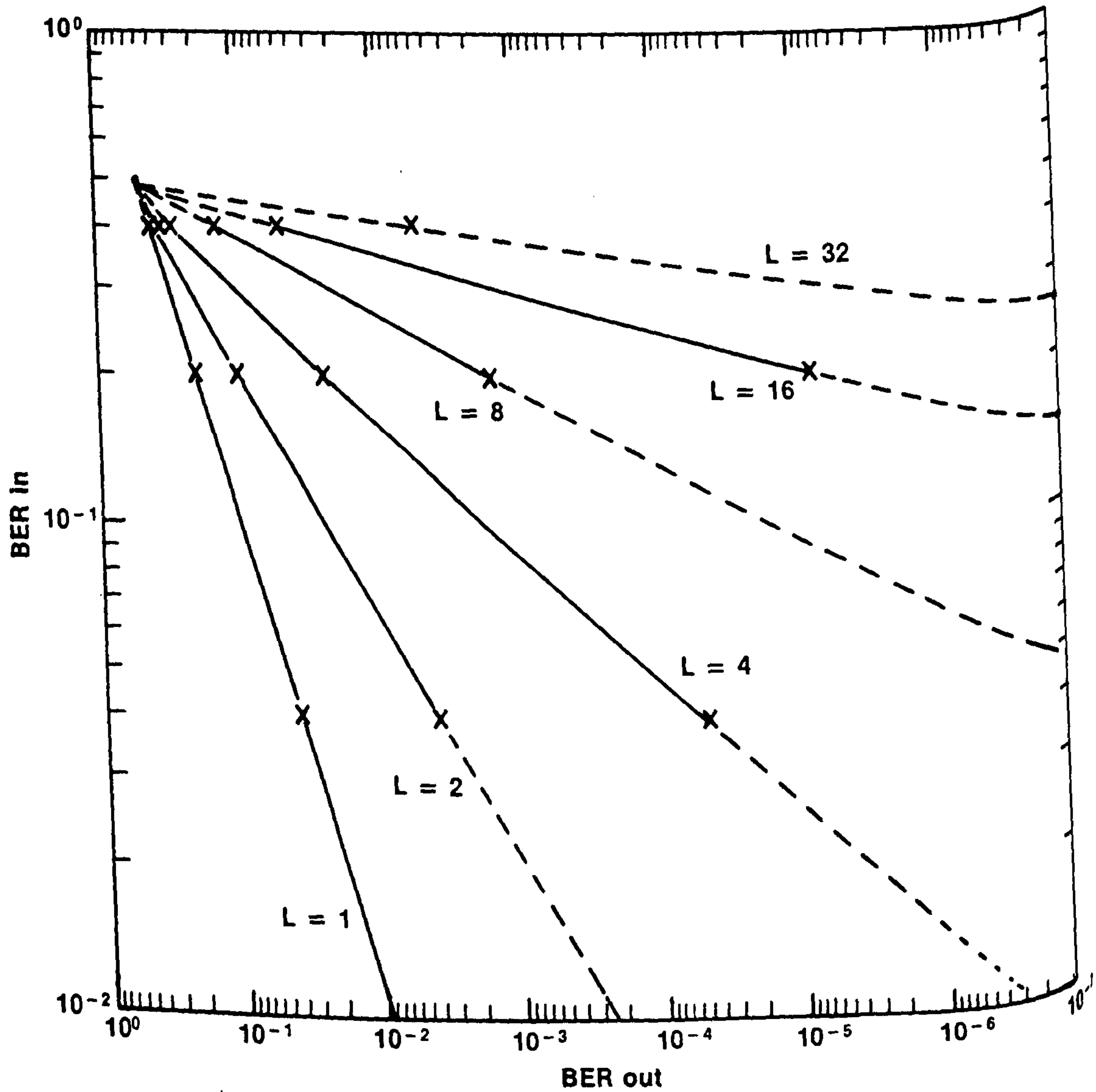


Fig. 5.2. $BER_{in}$ as a function of $BER_{out}$ for NED combining in the presence of PBN jamming plus noise at $SNR|_{eff}$ = 13.35 dB.

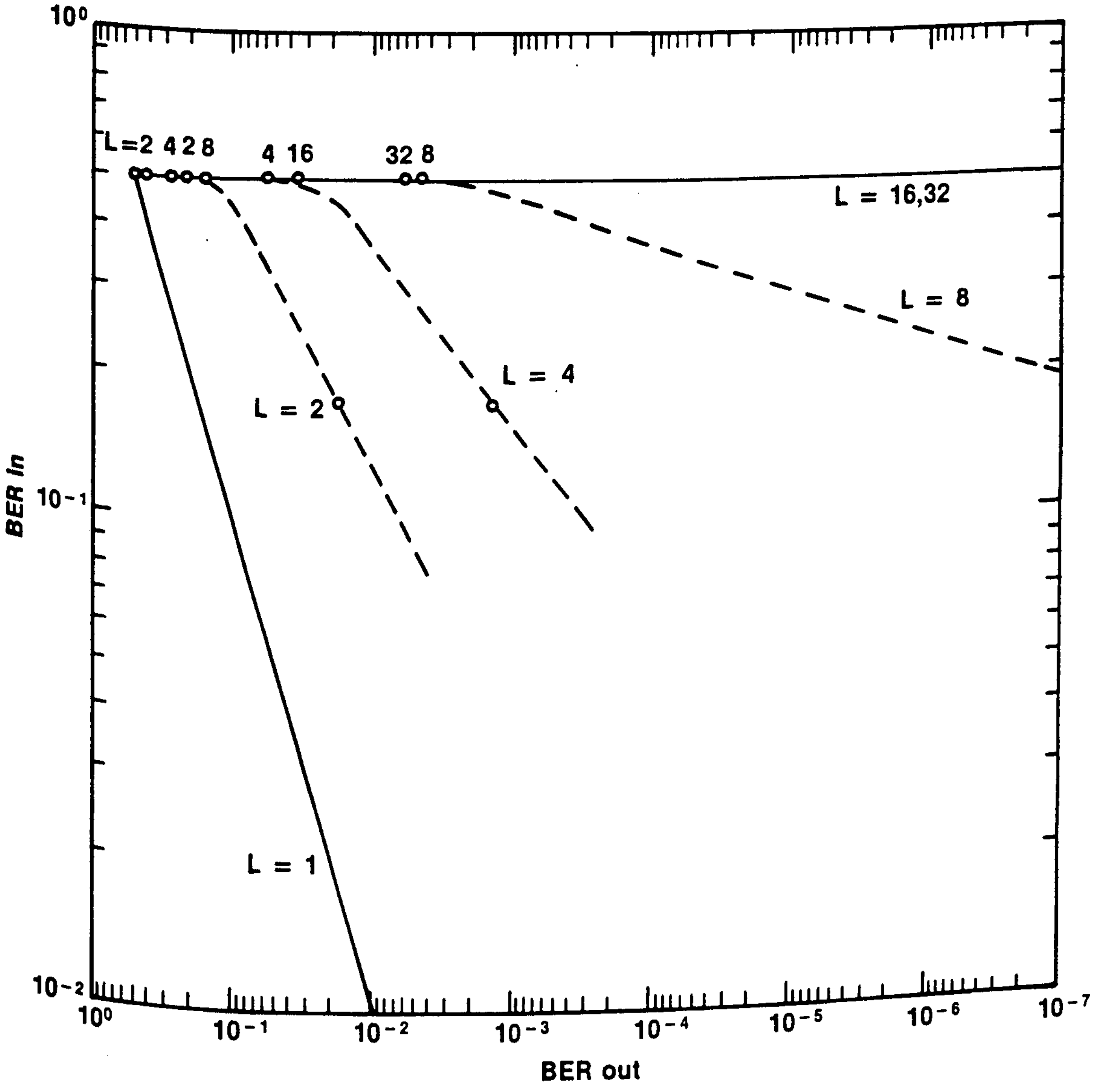


Fig 5.3. $BER_{in}$ as a function of $BER_{out}$ for NED combining in the presence of MT jamming plus noise at $SNR|_{eff}$ = 13.35 dB.

For Figs. 5.1 and 5.2, in the regions for $BER_{in}$<0.4, the curves on the log-log scale used are almost straight lines. Above $BER_{in} = 0.4$, the curves tend to curve upwards from the straight line projection indicating that the ability to correct errors decreases more rapidly.

The fact that the few points in Fig. 5.1 for MT jamming fall close to the curves for PBN jamming are easily explained. Only the points for $SJR_{MT} = 10$ dB are used. For this $SJR_{MT}$, the jamming tones are 1.0 dB below the signal tones and the background noise at SNR = 13.35 dB, is, therefore, relatively significant. Thus, the combined MT jamming and system noise is much like PBN jamming whence the points fall close to the PBN jamming curves.

For NED combining with MT jamming, an unexpected phenomenon was revealed by Fig. 5.3. As $BER_{in}$ is increased toward its maximum possible value of 0.5, the $BER_{out}$ increases as for the other cases in an approximately linear fashion on a log-log scale. However, the straight lines do not converge directly to the point ($BER_{out}$, $BER_{in}$) = (0.5, 0.5) Instead, a cut-off characteristic is exhibited. For values of $BER_{out}$ below the cut off value, the approximately linear (on a log-log scale) relationship pertains. However, above the cut-off value, the curve becomes horizontal close to the $BER_{in}$ = 0.5 line. The cutoff for L=16 and 32 are beyond $BER_{out} = 10^{-7}$. This observation implies that input error rates of very close to 0.5 can be corrected to give $BER_{out} = 10^{-7}$. This astonishing result can be explained by the great capability of NED combining to handle MT jamming. It is unfortunate results for SJR < 0dB were not obtained so that more details around the cut off region could have been obtained.

Further evidence of the capability of NED combining to handle MT jamming is seen in Fig. 5.3. For example, at L of only 4, a $BER_{in} = 0.1$ can be corrected to give a BER < $10^{-3}$.

## 5.3 Low-Rate Convolutional Codes

As an alternative to diversity combining, one can consider low rate EC coding. Unfortunately, we have measurement results for only r=1/2 convolutional EC coding. Shaft [4] considers low-rate convolutional codes with soft decisions where rates of r=1/2, 1/4, 1/8, 1/16, 1/32 and 1/64 were studied. To compare diversity combining and coding, the coding redundancy, 1/r is equivalent to the level of the diversity, L. Unfortunately, Shaft's [4] analysis is not directly applicable here because he considered soft decisions and because he used bounding analysis that is appropriate only in the region of low $BER_{in}$. By contrast, in the present application, soft decision operation should be avoided because of its vulnerability to changing jammer strategy. Also, the present application is in the high $BER_{in}$ region just where Shaft's analysis becomes inappropriate. Nonetheless, it seems to be implied in [4] that the BER of a rate r code in the presence of AWGN can be found by taking the measured performance curve of the rate r=1/2 curve shown in Fig. 4.1 and shifting it by 10 log 2r dB. Therefore, we calculated lower code-rate performance based upon, first, shifting the coding curve in Fig.4.1. by 10 log 2r dB. Then for a particular SNR, the BER for the codec was taken as $BER_{out}$ and the corresponding BER for the uncoded signal was taken as $BER_{in}$. It is cautioned that it is not certain that this approach is valid especially at very high $BER_{in}$. Experimental verification is needed.

The results for coding at r=1/2, 1/4, and 1/8 with AWGN are shown in Figs. 5.4, 5.5 and 5.6, respectively. For comparison to the same level of redundancy, results for diversity combining for L=2, 4 and 8 are also plotted. The results for HDMV combining for PBN jamming at L=2,4, and 8 are taken from Fig. 5.1 and replotted in Figs. 5.4, 5.5 and 5.6, respectively. Similarly, the performance for NED combining for both PBN and MT jamming are replotted from Figs. 5.2 and 5.3 respectively.

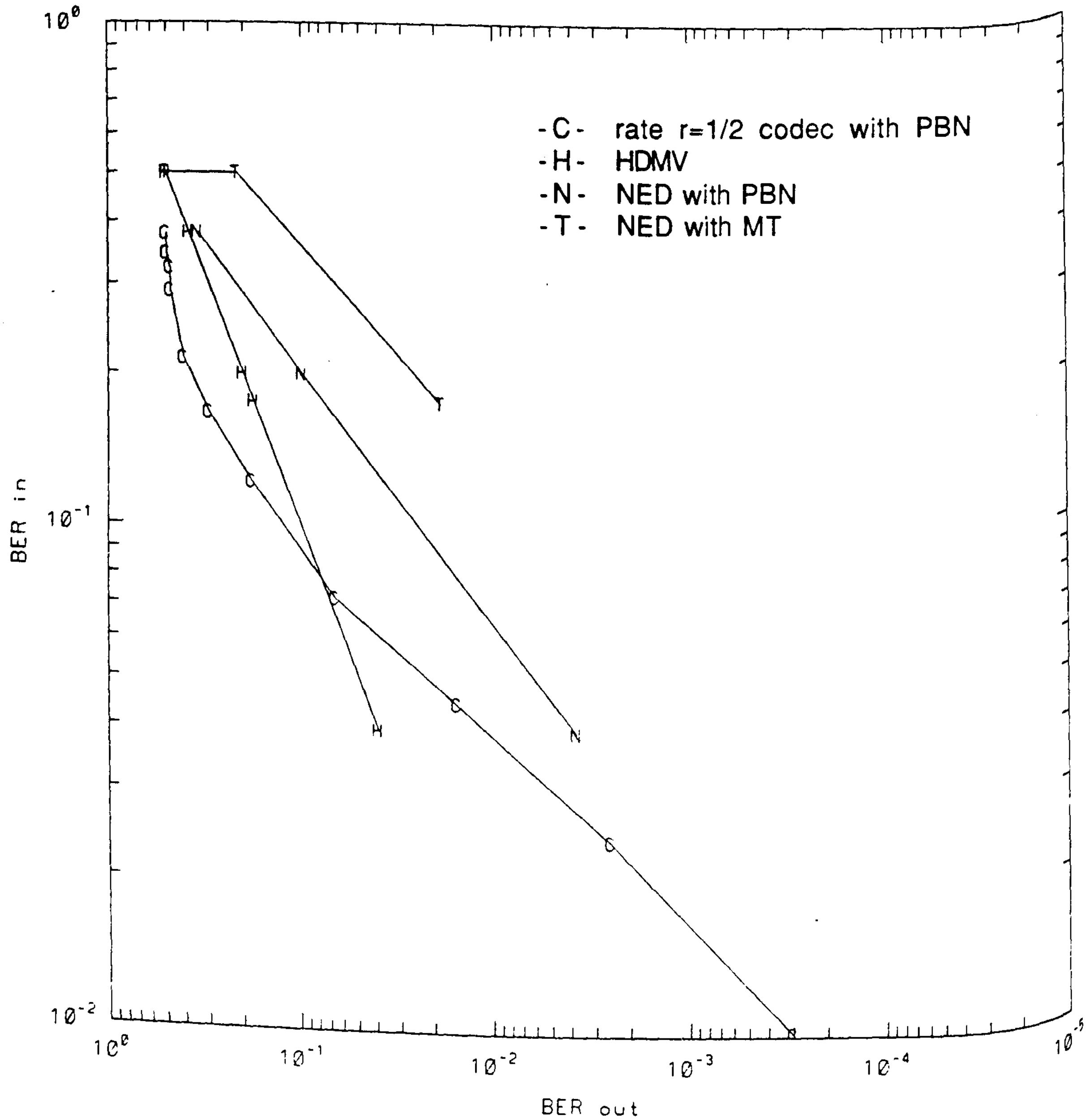


Fig. 5.4. $BER_{in}$ as a function of $BER_{out}$ for a redundancy of 2.

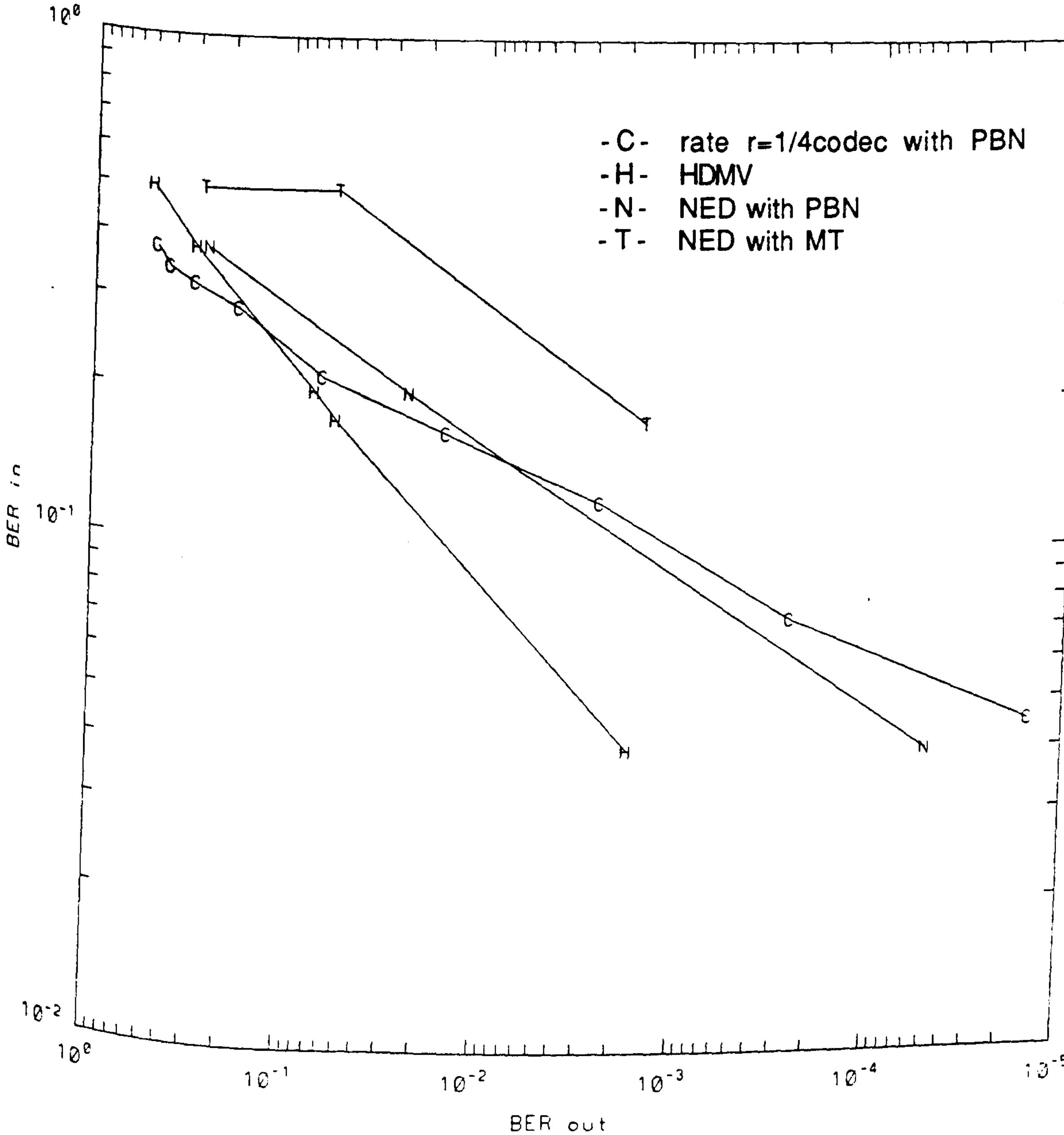


Fig. 5.5. $BER_{in}$ as a function of $BER_{out}$ for a redundancy of 4.

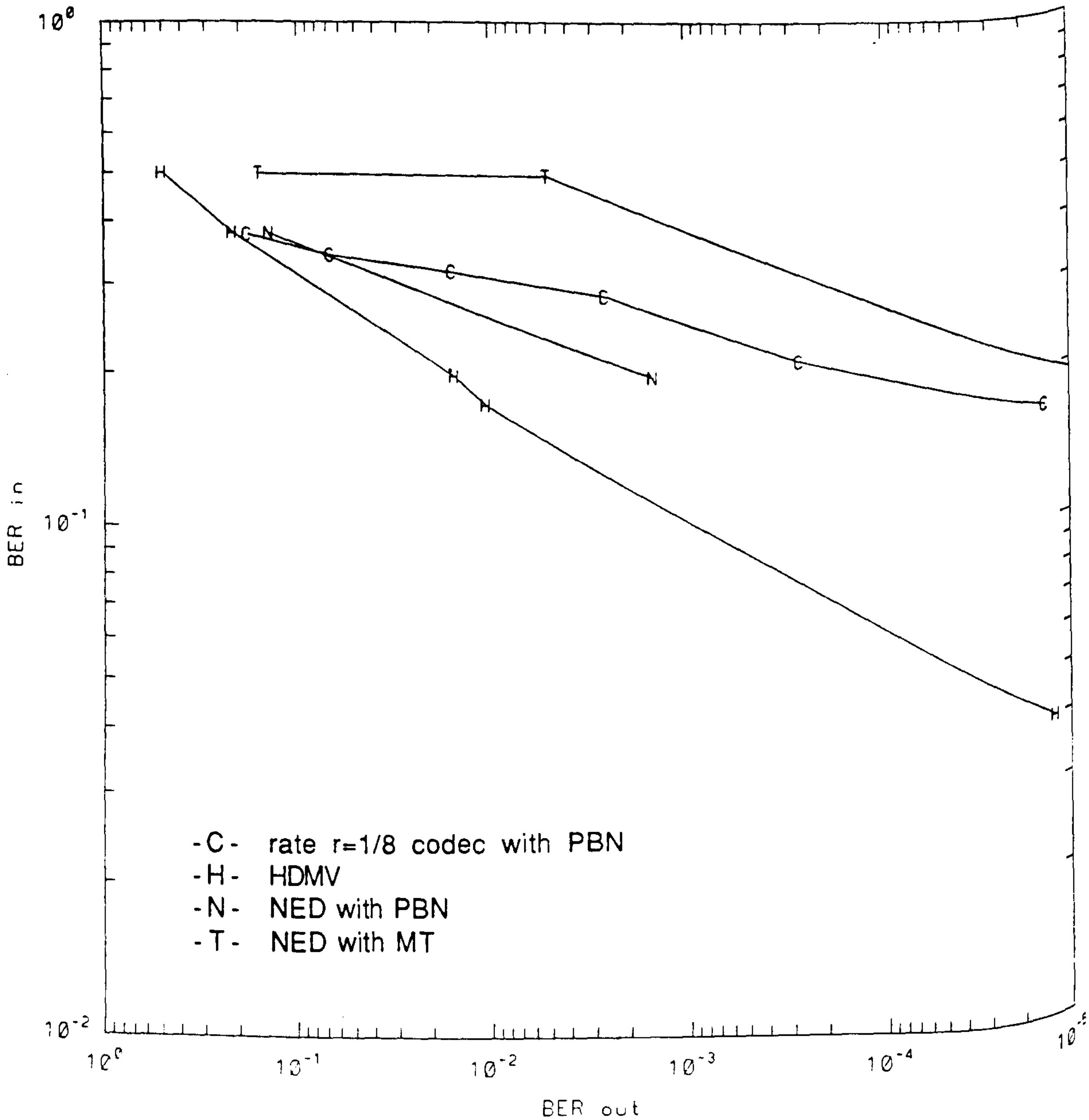


Fig. 5.6 $BER_{in}$ as a function of $BER_{out}$ for a redundancy of 8.

In comparing coding to HDMV combining, both with AWGN, a redundancy of 2 reflects Fig. 4.1 in that the coding gives better performance for $BER_{in} < 0.1$, and HDMV gives better performance above 0.1. For a redundancy of 4, the cross-over $BER_{in}$ increases to about 0.3, and for a redundancy of 8, the cross over is close to the maximum possible $BER_{in}$ of 0.5.

In comparing coding to NED, both with AWGN, at a redundancy of 2, the NED combining far out performs the coding for $BER_{in} > 0.02$. For a redundancy of 4, the NED out performs the coding for $BER_{in} > 0.2$ and has identical performance over the range of $BER_{in}$ between 0.05 and 0.2. For a redundancy of 8, the coding outperforms NED for $BER_{in} < 0.3$ and appears to be equal for $BER_{in} > 0.3$.

Finally, the performance of coding with AWGN is compared to that of NED with MT jamming. For all values of redundancy, the NED is seen to out perform considerably the coding for $BER_{out} \geq 10^{-5}$. This result is all the more remarkable because if the coding had to handle the same MT jamming that the NED is handling instead of the AWGN, it is thought that the coding performance would drop even more.

From Figs. 5.4 to 5.6 it could be concluded that for the highest values of $BER_{in}$, the NED gives better performance against PBN jamming but at lower $BER_{in}$, the coding becomes slightly better in performance than NED. Also, NED likely does very much better against MT jamming than does coding. Since these conclusions are based on the assumption that the coding performance increases as 10 log 2r, it is cautioned that the coding performance given above could actually be optimistic especially at low $BER_{in}$. Finally, the number of computations required in the Viterbi decoding goes up linearly with a decrease in the code rate whereas the complexity of NED combining is independent of L. Thus, overall, it appears that for the present application, NED is the preferred method.

## 6.0 CONCLUSION

Both HDMV and NED combining have been implemented in hardware and operated in real time with diversity levels between 1 and 32. Extensive error rate measurements have been made.

HDMV combining is attractive because of its great ease of implementation. Hardware consists simply of comparators and adders. It is also attractive because of its capability of easily changing the value of L, and its adequate performance in the presence of PBN jamming. It fails to perform against MT jamming at low SJR.

NED combining is more complex to implement than HDMV combining because it requires mathematical divisions. Fortunately, some form of digital signal processing (DSP) chip, such as the TMS 320-C25 used here, is adequate to perform all the needed processing. Also, the complexity does not change with L and the value of L can be easily changed. The error correction capability of NED against PBN jamming is reasonably good and either equals or surpasses that of the corresponding low-rate coding for the high levels of $BER_{in}$ considered here. The error-correction capability of NED against MT jamming is exceptionally good. It is conjectured that only some other non-linear combining technique could even compare to the performance of NED but not exceed it.

Low-rate coding has an error-correction capability against PBN jamming that is slightly inferior to NED at the high values of $BER_{in}$ of interest here. The redundancy level of low-rate coding is not easily changed to meet changing conditions. It is also complex to implement for the lower rates, likely being more complex than NED to implement.

Overall, NED combining is the recommended method to achieve performance enhancement in the presence of large jammers that can use either PBN or MT jamming.

## 7. REFERENCES

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# APPENDIX "A"

# CIRCUIT DIAGRAMS

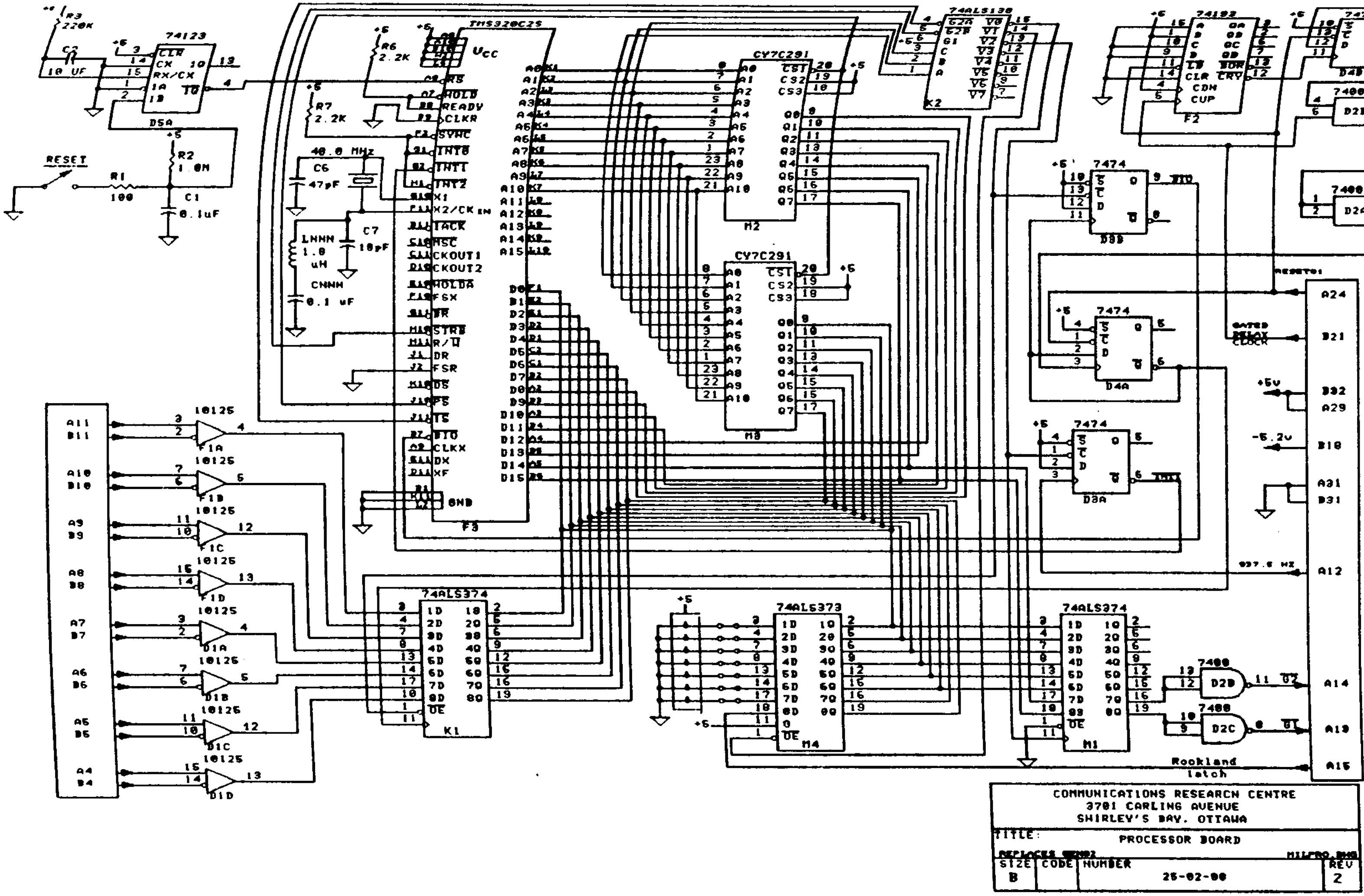


Fig. A1. The TMS 320 decision-device processor board.

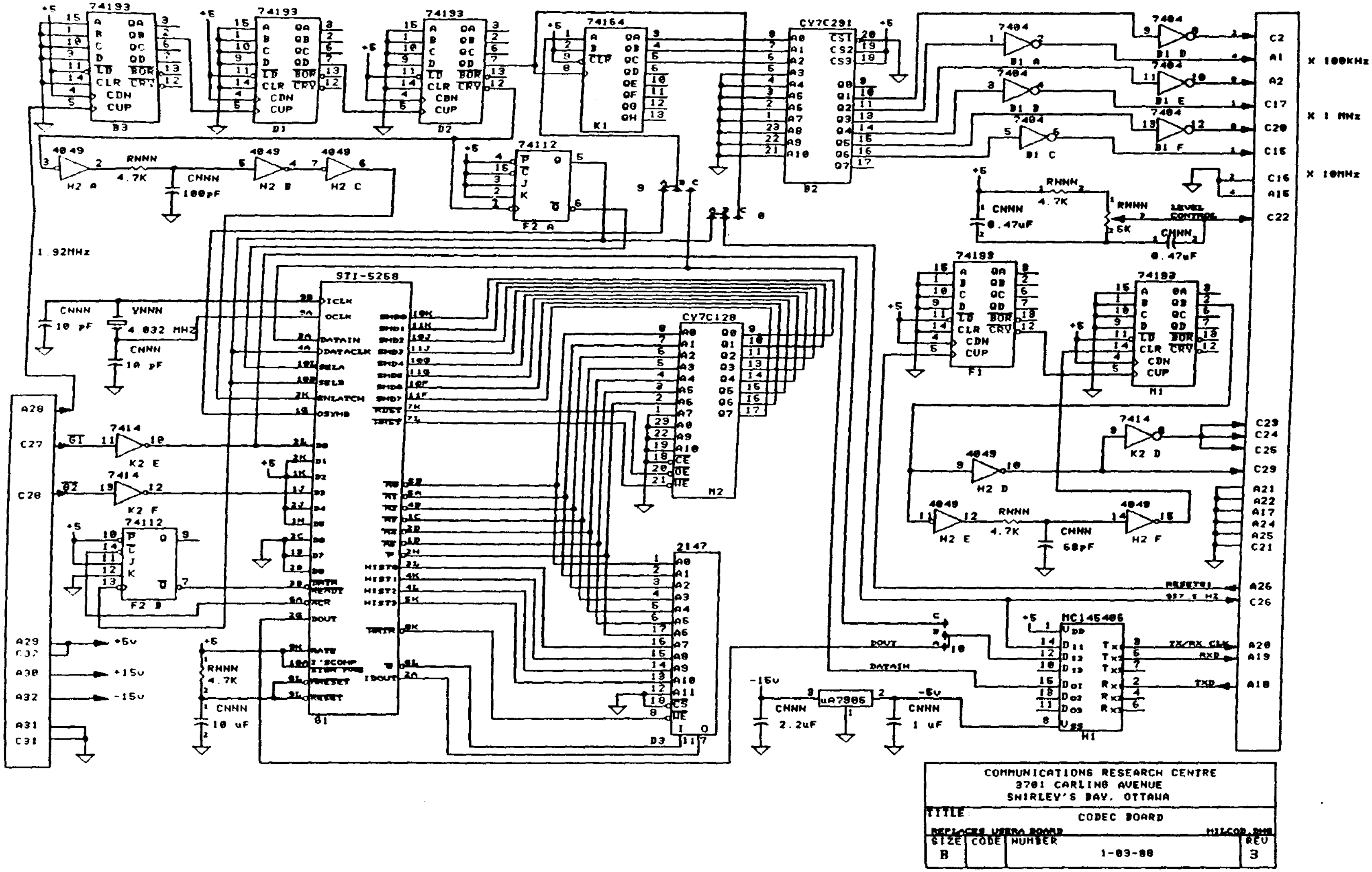


Fig. A2. The rate r=1/2, K=7 codec board.

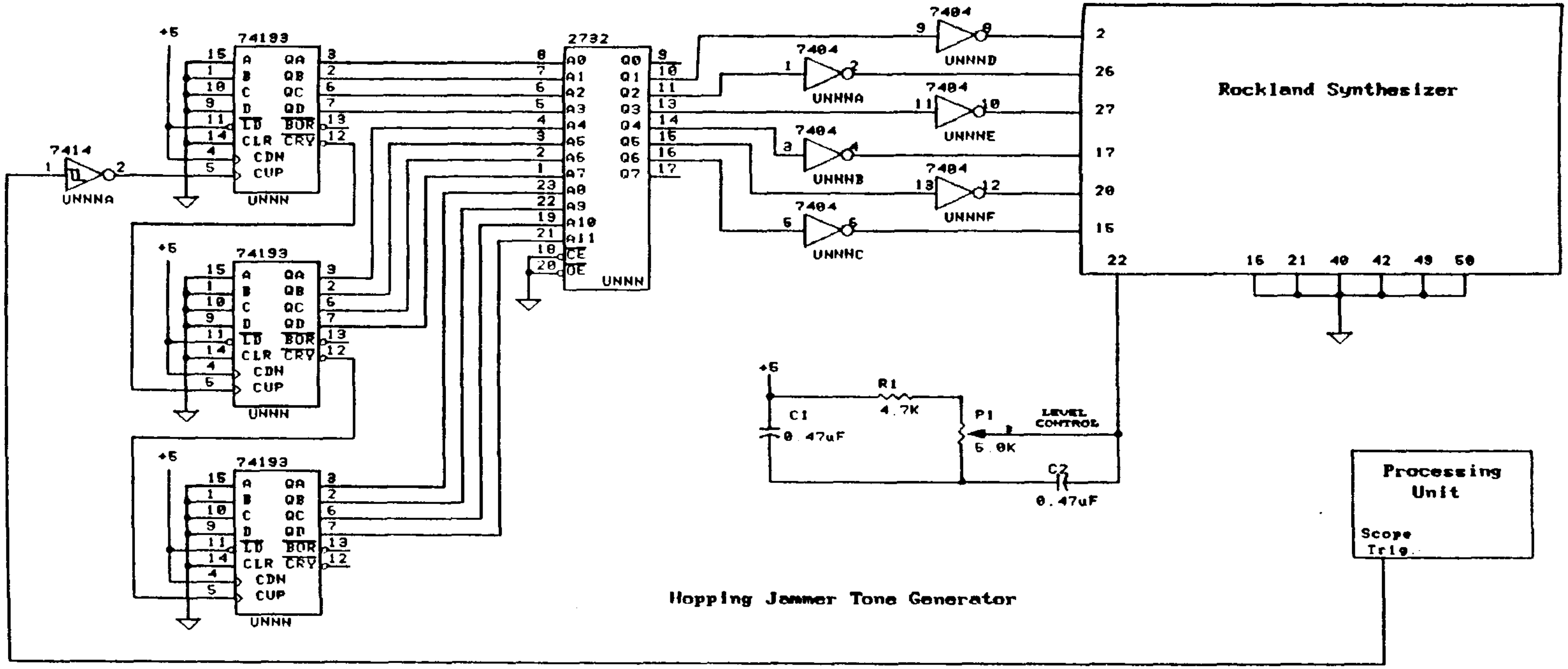


Fig. A3. Random jammer tone generator.

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A micro-processor based signal processor was built and tested capable of performing the diversity combining needed to reduce the error rate of 8-ary non-coherent FSK signals demodulated onboard a satellite. Two combining techniques were implemented and tested: hard decision majority vote (HDMV) and normalized envelope detection (NED). Measurements of bit error rate performance of these two techniques in the presence of system noise plus either partial-band noise (PBN) or multiple tone (MT) jamming were made for levels of diversity, L, from 1 to 32. The SJR levels used were so low that worst-case jamming was always with the full band jammed. Results showed that HDMV combining could give error correction for PBN jamming for a SJR as low as 0 dB but gave no correction for MT jamming when SJR was less than 10 dB even for L as high as 32. NED combining handled PBN jamming better than the HDMV and performed very well against MT jamming even at a SJR as low as 0 dB. Results show for the low SJR regime considered, that NED combining is clearly the error correction method of choice over HDMV combining and over low rate coding.

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frequency-hopping,
spread spectrum,
anti-jam communications,
satellite communications,
onboard processing,
surface-acoustic wave processors,
diversity combining,
error correction

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