VHF AND HF FIELD TESTS WITH AN INTERLEAVED 1/3 RATE BLOCK CODE

J. R. JUROSHEK
Office of Telecommunications
Institute for Telecommunication Sciences
Boulder, Colorado

Summary A one-way error correcting system that employs a onethird rate, interleaved, block code was constructed and tested at teleprinter speeds. All system functions including timing and synchronization were tested over a 1300 km VHF ionoscatter path and a 1500 km HF path. The decoder used "minimum-distance decoding." The results showed that coder performance was close to theoretical predictions. A useful secondary output, called the inversion count, was analyzed. A difference in coder performance was noted between the VHF and HF channels.

Introduction The Institute for Telecommunication Sciences has recently conducted a coding experiment consisting of engineering design, implementation, and field testing of an interleaved and block-coded error control system [1] . The coder/decoder was designed for 60 to 100 word per minute (wpm) teleprinter (TTY) and was tested over an existing VHF ionospheric scatter path and an HF path. All the necessary synchronization and timing were derived from the received signal.

The block code selected was the three-error, correcting (15, 5) Bose-Chaudhuri-Hocquenghem (BCH) code with a three-to-one redundancy [2], [3]. Each coded word (codeword) was composed of n = 15 bits of which k = 5 were the information bits of a standard Baudot TTY character. The start and stop bits were not transmitted by the system. The remaining 10 bits were parity bits generated by a linear, five-stage, shift register.

To counteract the slow fading normally encountered on the two test circuits, 64 bits of interleaving were used. If A_1 A_2 A_3 A_4 A_5 were the information bits of the first TTY character, and A_6 -A_{15} were the parity bits, then the transmitted codewords are in the form,

$$A_1\ B_1\ C_1 \ldots A_2\ B_2\ C_2 \ldots A_3\ B_3\ C_3 \ldots \ldots A_{15}\ B_{15}\ C_{15} \ldots,$$

where the A's were separated from other A's by 63 bits from other codewords. The process of interleaving and encoding was accomplished simultaneously by the interleaver-encoder shown in Fig. 1.

A group of 64 coded and interleaved TTY characters was called a frame and consists of 64 x 15 = 960 bits. To maintain sync at the receiving terminal, a special uncoded 64 bit frame sync sequence was inserted after each frame. This sequence was a 63-bit maximum length sequence extended to 64 bits by retransmitting the first bit. Since errors may occur during the transmission of this sync character, the decoder had provisions for updating the frame sync clock without the full 64 bits being received correctly. Experience during the actual tests showed that at least 58 bits of "match" should be required before updating of the frame timing took place.

To avoid teleprinter slowdown, the system sacrificed bandwidth to transmit the redundant information. For a normal 60 wpm (50 bit/sec) TTY, the encoder output rate was 108 bits/sec. An interleaved 15-bit codeword spanned 8.4 sec, as compared with 0.14 sec without interleaving.

At the decoder terminal the incoming frame was uninterleaved and decoded using "minimum distance" or "maxirnum likelihood decoding." The decoder had plenty of time to scan the $2^5 = 32$ possible 15-bit codewords and determine which codeword was nearest to the received sequence. A block diagram of the decoder is shown in Fig. 2. The number of bit inversions i, that was performed on the received character to realize the nearest codeword was also available.

Test Procedures For this series of tests a special repetitive random looking sequence of 64 TTY characters was continuously transmitted. At the receiving terminal, the decoded 5-bit characters were sequentially recorded on magnetic tape along with the 4 bits of inversion count i. Each of these characters was compared with the transmitted character by a computer and classified as correct with i inversions C(i), or in error with i inversions E(i). The results were then tabulated for a number of 10-minute samples composed of J= 4032 TTY characters. It may be shown that none of the 2^{15} possible received sequences can have a nearest codeword at a distance of 6 or greater. Thus in a 10-minute sample

$$\sum_{i=0}^{5} [C(i) + E(i)] = J .$$

Although we were not able to measure directly the channel bit error probability, P_e, we were able to estimate it from the C(i) and E(i) data. The fraction A bits in error must satisfy two obvious bounds

$$\frac{1}{15J}\left[\sum_{i=1}^{5} i\,C(i) + \sum_{i=0}^{5} i^{*}\,E(i)\right] \le p_e \le \frac{1}{15J}\left[\sum_{i=1}^{5} i\,C(i) + 15\sum_{i=0}^{5} E(i)\right],$$

where i* is defined as i = max {7-i, 4}. These bounds proved to be a sharp estimate of P_e, provided

$$\sum_{i=0}^{5} E(i) << \sum_{i=1}^{5} C(i).$$

We used the average (arithmetic mean) of the two bounds $\overline{P}_e$, as an estimate of P_e . A typical example of the closeness of the bounds for the $\overline{P}_e$ estimate is shown in Table I.

TABLE I

TYPICAL LOWER AND UPPER BOUNDS FOR $\overline{P}_e$

$\overline{P}_e$	Lower Bound	Upper Bound
2.05×10^{-1}	1.30×10^{-1}	2.80×10^{-1}
1.32×10^{-2}	1.24×10^{-2}	1.40×10^{-2}
1.92×10^{-3}	1.92×10^{-3}	1.92×10^{-3}

Test Results The VHF transmissions took place from Long Branch, Illinois, to Boulder, Colorado, at a frequency of 49.64 MHz. This type of propagation could be characterized as Rayleigh fading supported by scatter from the D region. Superimposed on this were recognizably bursts of signals from meteors and occasionally sporadic-E reflections [4], [5]. The tests were conducted with dual diversity rhornbic, single rhombic, dual Yagi, and single Yagi receiving antennas. Each rhornbic had a gain of approximately 20 dB and the yagi approximately 9 dB. The radiated power was nominally 500 watts and the transmissions were NCFSK with a 6 kHz frequency deviation. Three different samples of the recorded AGC from one diversity receiver are shown in Fig. 3.

The HF tests took place between the Naval Postgraduate School at Monterey, California, and the Boulder terminal. During the night a frequency of 5.9265 MHz was used and during the day, 13.56 MHz. At night the most probable modes of propagation were single or multi-hop reflections from the E layer, and during the day single or multi-hop reflections f roin the F layer [6] . Fading on this type of channel is generally characterized as Rayleigh or Nakagami-Rice. The HF tests were conducted with 100 watts of radiated power, NCFSK transmission and a frequency deviation of 850 Hz. The antenna was a base-loaded 32-ft vertical. whip.

One of the foremost quantities to be measured was the word error probability after decoding, which can be obtained from the expression

$$P_E \text{ (Coded)} = \frac{1}{J} \sum_{i=0}^{5} E(i).$$

This represents the probability that a TTY codeword is incorrectly de coded. In Fig. 4 the results are shown for the VHF tests with dual diversity rhombics. Each point on the graph represents the results of a 10-minute sample. The solid curve represents the theoretical calculations for a memoryless binary symmetric channel (BSC) with “hard sphere” decoding and is given by

$$P_E \text{ (Coded BSC)} = \sum_{n=4}^{15} \binom{15}{n} \bar{p}_e^{\,n} (1 - \bar{p}_e)^{15-n} .$$

As can be seen, this type of decoder is reasonably descriptive of our data.

Another quantity of interest is the probability of error for a 15-bit codeword prior to decoding (uncoded). This quantity, shown in Fig. 5, is given by

$$P_E \text{ (Uncoded)} = \frac{1}{J} \left[\sum_{i=1}^{5} C(i) + \sum_{i=0}^{5} E(i) \right],$$

along with its theoretical BSC counterpart

$$P_E \text{(Uncoded BSC)} = 1 - (1 - \bar{p}_e)^{15}.$$

Although a number of definitions of improvement factor exist, in this report it is defined as

$$F = \frac{P_E \text{ (Uncoded)}}{P_E \text{ (Coded)}} .$$

As shown in Fig. 6, the quantity was infinite for $\bar{p}_e \leq 10^{-2}$ since all codewords in a nominal 10-minute sample were corrected.

The error probability of an individual TTY output bit, P_E(TTY Bit), was also measured and is shown in Fig. 7. These measurements agree with the theoretical predictions for a BSC channel [7] ,

$$P_E \text{ (TTY Bit BSC)} = \frac{2^{k-1}}{2^k - 1} P_E \text{ (Coded BSC)},$$

where k is the number of bits per TTY character (k = 5 in these tests).

The VHF results with other antenna configurations (such as single rhombic, dual Yagi, and single Yagi) were quite similar to the previous tests and need not be described in length. This was also true for the HF tests. As an example, P_E (coded) for the dual Yagi VHF tests and 5.9265 MHz HF tests are shown in Figs. 8 and 9. As can be seen, the HF data samples seem to have more spread and at times poorer performance.

The fraction of codewords received correct or in error in a 10-minute sample is given by $\frac{1}{J} C(i)$ and $\frac{1}{J} E(i)$, respectively. As one might expect these results are strongly dependent on $\overline{p}_e$ for that particular sample. In Fig. 10, $\overline{C(i)} / \overline{E(i)}$ is shown as a function of i, where $\overline{C(i)}$ and $\overline{E(i)}$ are the arithmetic means of C(i) and E(i) averaged over a selected population of 10-minute samples with a wide range of $\overline{p}_e$. This type of data estimates the odds of a decoded codeword being correct given a known i. The information should be valuable to a user who can observe i, but has no knowledge of the channel bit error probability $\overline{p}_e$. The results are shown for dual diversity rhombic antennas, dual Yagi's, and the two different HF frequencies. As can be seen, a definite pattern exists. The trends can be attributed to differences in fading characteristics. With its wider antenna pattern, the dual Yagi signal should contain more meteor reflections than the dual rhombic. Similarly the average fading rate from E layer reflections is likely to be slower than from F layer. Note that with an inversion count of i = 3 the odds on the decoded character being correct were less than 2.5 to 1.

Conclusions The severely fading VHF ionoscatter and HF channels were used to test a 60 wpm coded TTY. The equipment was specifically designed and constructed for the tests. The results from approximately 300 hours of tests were summarized in a number of graphs. The experiment showed that theoretical predictions for a memoryless binary symmetric channel with hard sphere decoding were reasonably descriptive of the actual measurements. The measurements of $\overline{C(i)} / \overline{E(i)}$, showed a marked difference between the dual rhombic and dual Yagi tests, as well as the 13.56 MHz daytime measurements over the 5.9265 MHz nighttime tests. The coding and interleaving was most effective in debursting the errors in the VHF dual rhombic tests and least effective in the 5.9265 MHz HF tests. None of the 10-minute samples examined had decoded character errors when $\overline{p}_e \leq 10^{-3}$.

References

[R. J. Matheson and M. Nesenbergs, “An encoder and minimum distance decoder for teleprinter channels with error bursts,” U.S. Dept. of Commerce, Institute for Telecommunication Sciences, Boulder, Colorado, ESSA Tech. Memo. ERLTM-ITS 249 (unpublished), August 1970.

[2] W. W. Peterson, “Error-Correcting Codes,” New York: M. I. T. Press and John Wiley & Sons, 1961.

[3] R. G. Gallager, “Information. Theory and Reliable Communication,” John Wiley and Sons, Inc., New York, N.Y., 1968.

[4] JTAC Report on Scatter Transmissions, “Ionospheric scatter transmission,” Proc. IRE, vol. 48, pt. 1, pp. 5-29; January 1960.

[5] J. W. Koch, “Modulation studies for VHF ionospheric scattering,” NBS Report 5597, pp. 1-35, August 1958.

[6] K. Davies, “Ionospheric Radio Propagation,” U.S. Dept. of Commerce, National Bureau of Standards, Monograph 80, 1965.

[7] A. J. Viterbi, “Principles of Coherent Communications,11 McGraw-Hill Book Company, New York, N.Y., 1966.

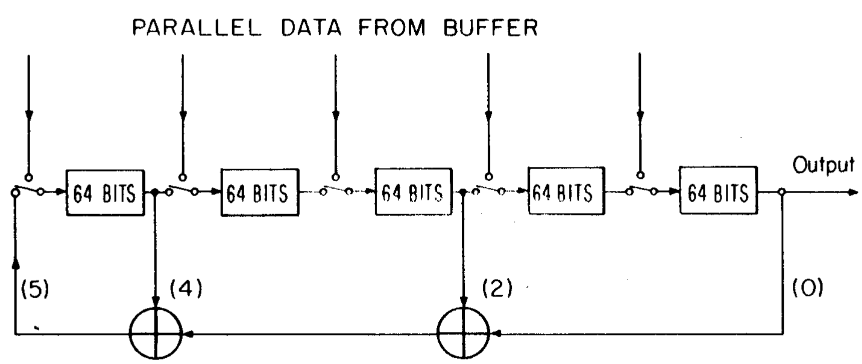


Fig. 1 - Interleaver- Encoder

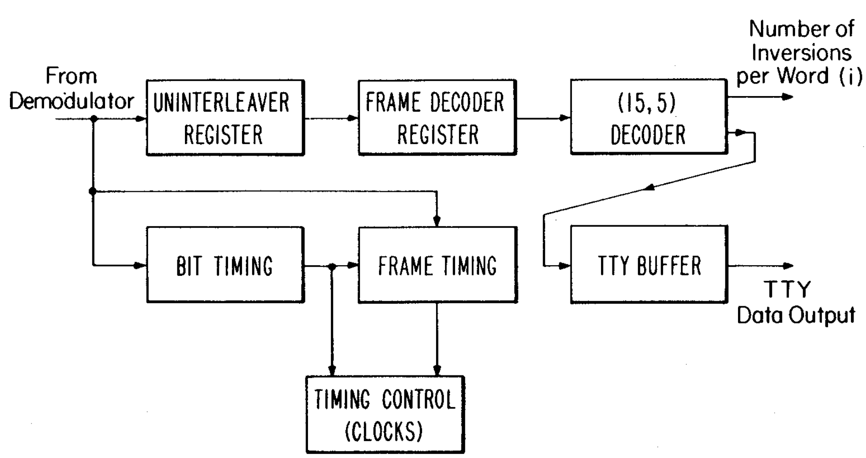
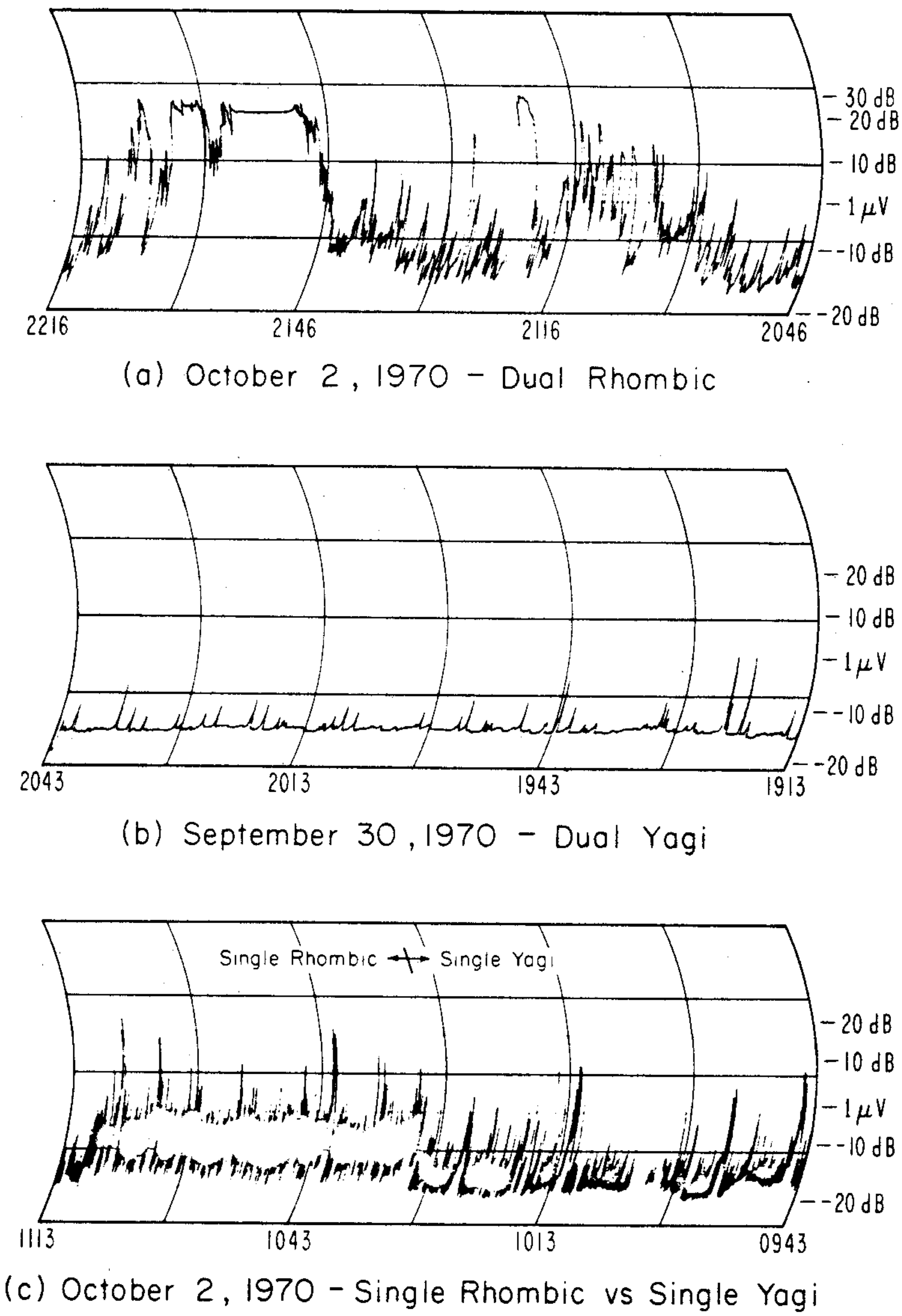


Fig. 2 - Uninterleaver-Decoder Terminal



(a) October 2, 1970 – Dual Rhombic

(b) September 30, 1970 – Dual Yagi

(c) October 2, 1970 – Single Rhombic vs Single Yagi

Fig. 3 - Recorded AGC from a Single Diversity Receiver

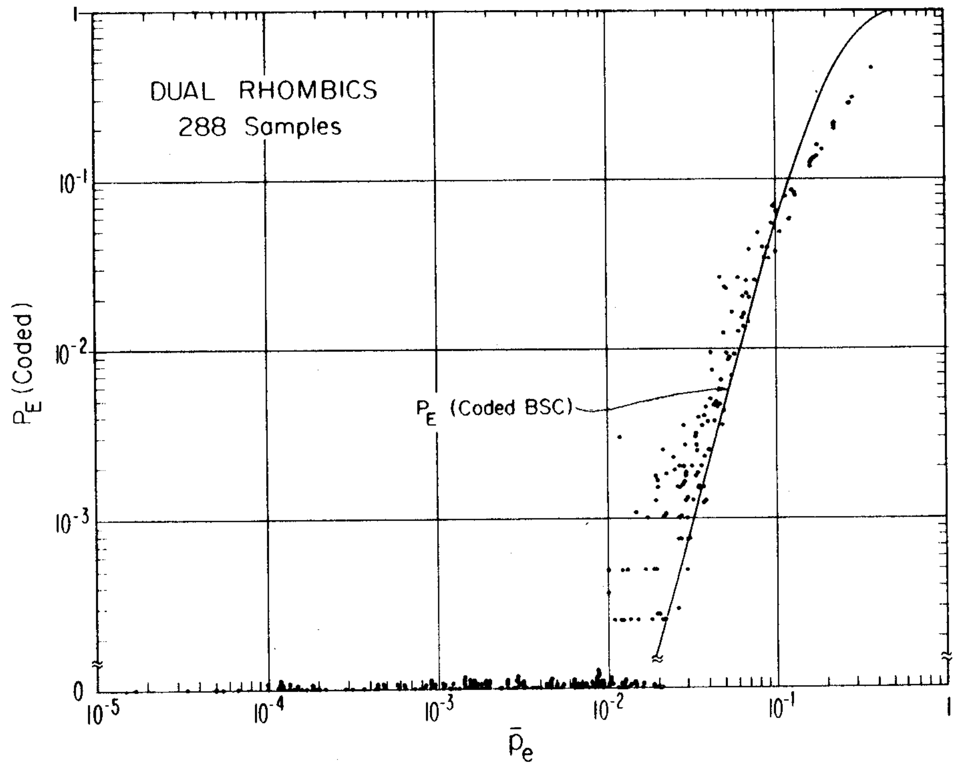


Fig. 4 - Word Error Probability for a Decoded 15 Bit TTY Codeword Versus Channel Bit Error Probability

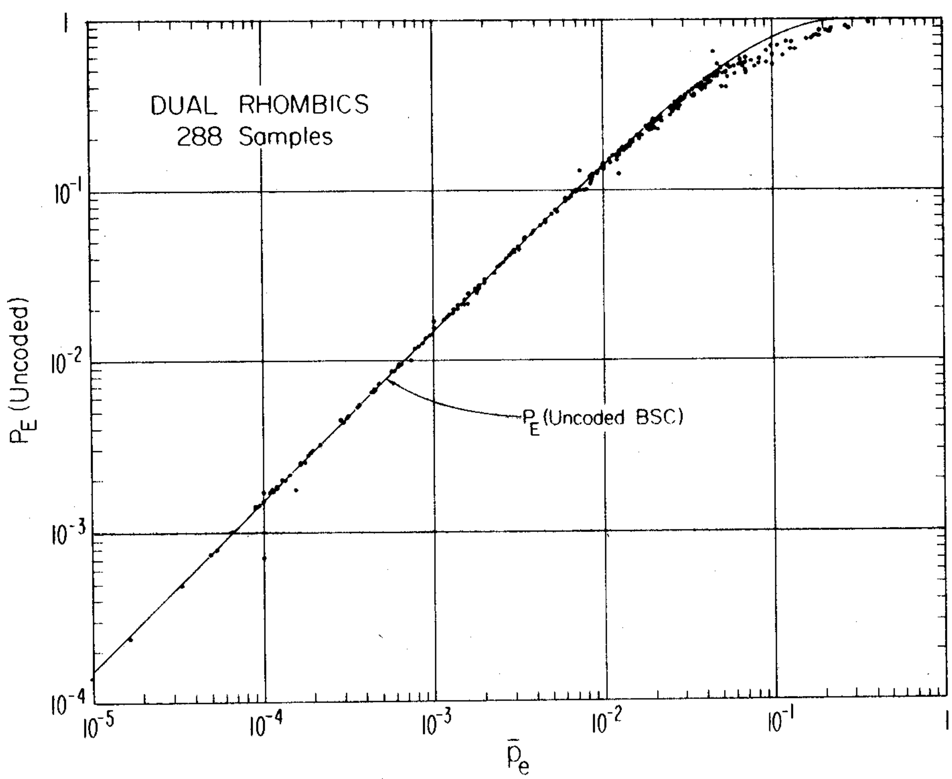


Fig. 5 - Word Error Probability Prior to Decoding for a 15 Bit TTY Codeword Versus Channel Bit Error Probability

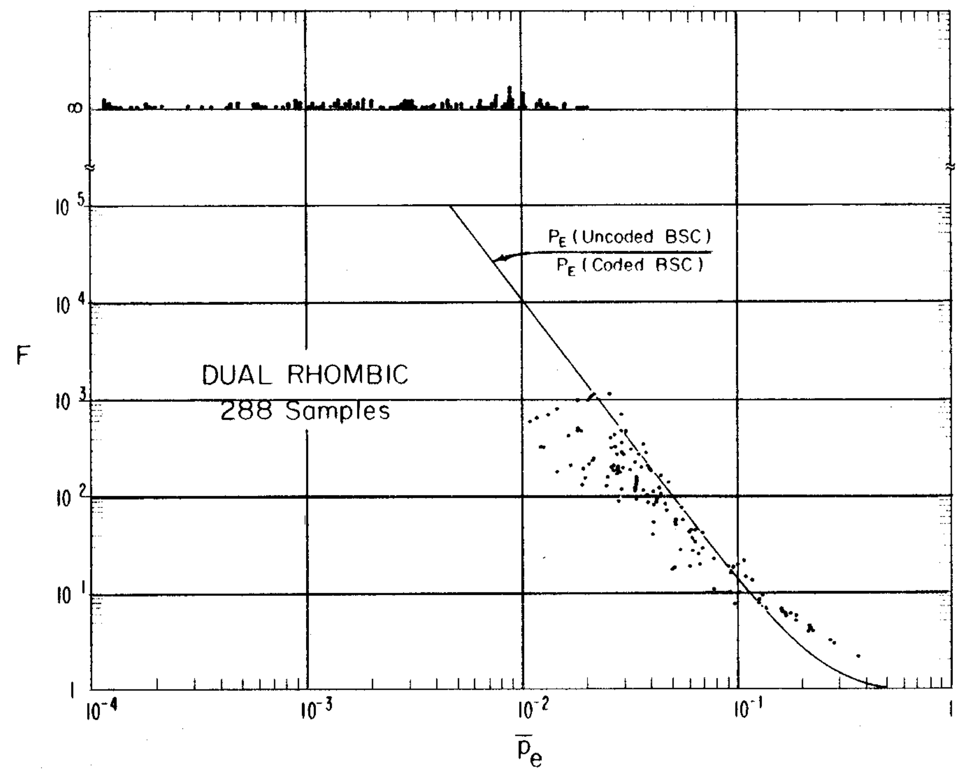


Fig. 6 - Improvement Factor F Versus Channel Bit Error Probability

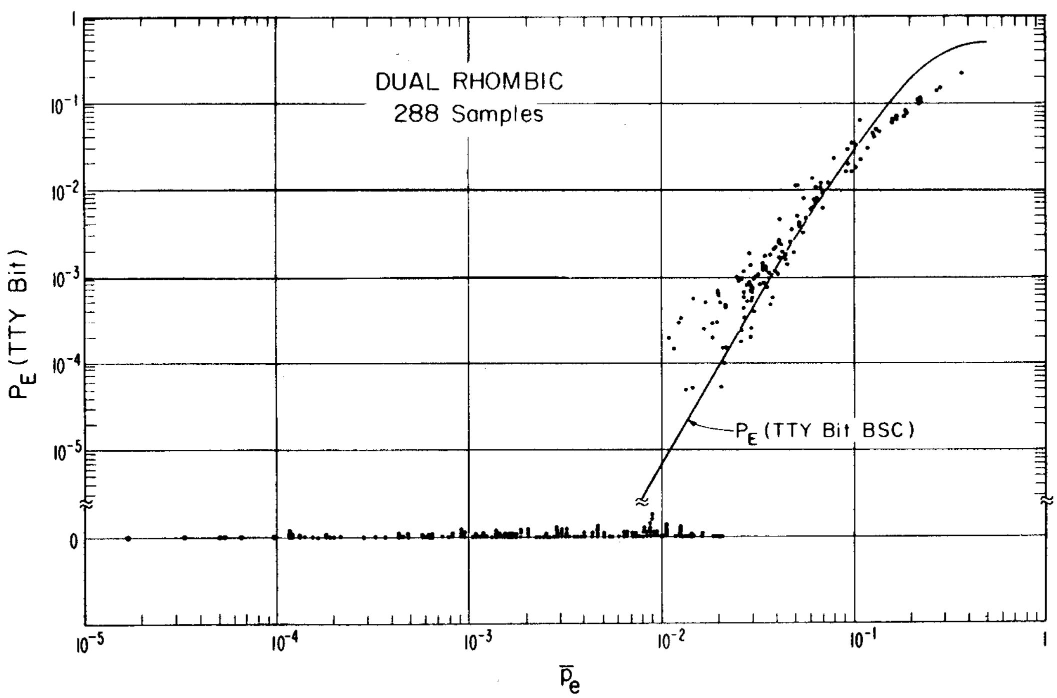


Fig. 7 - Probability of a TTY Bit Error After Decoding Versus Channel Bit Error Probability

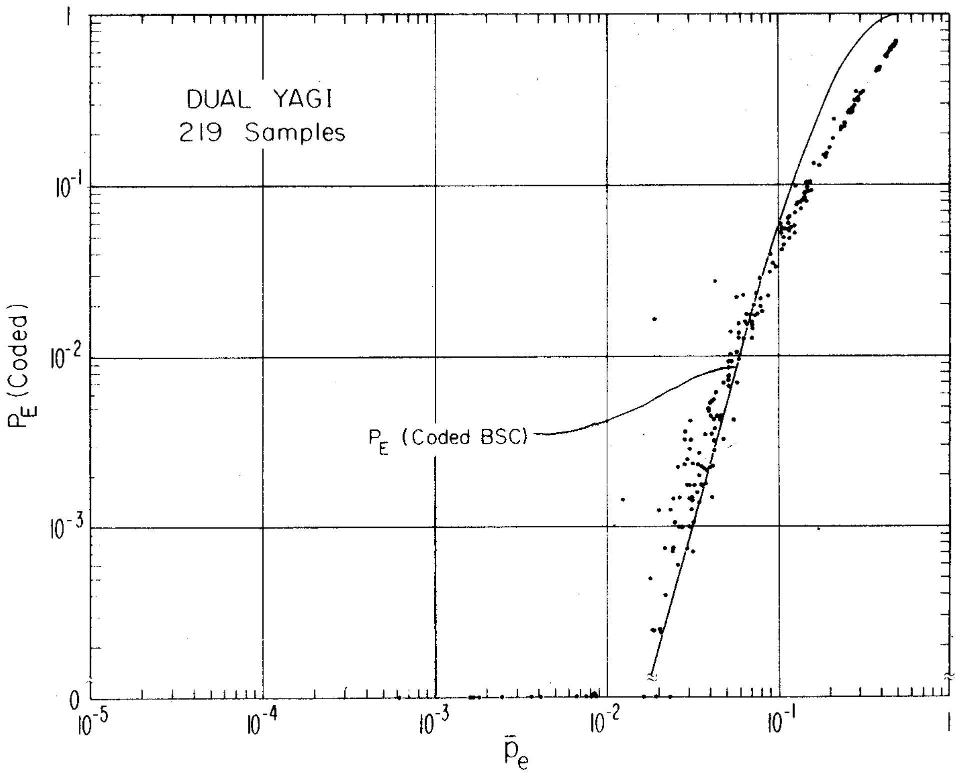


Fig. 8 - Word Error Probability for a Decoded 15 Bit TTY Codeword During the Dual Yagi VHF Measurements

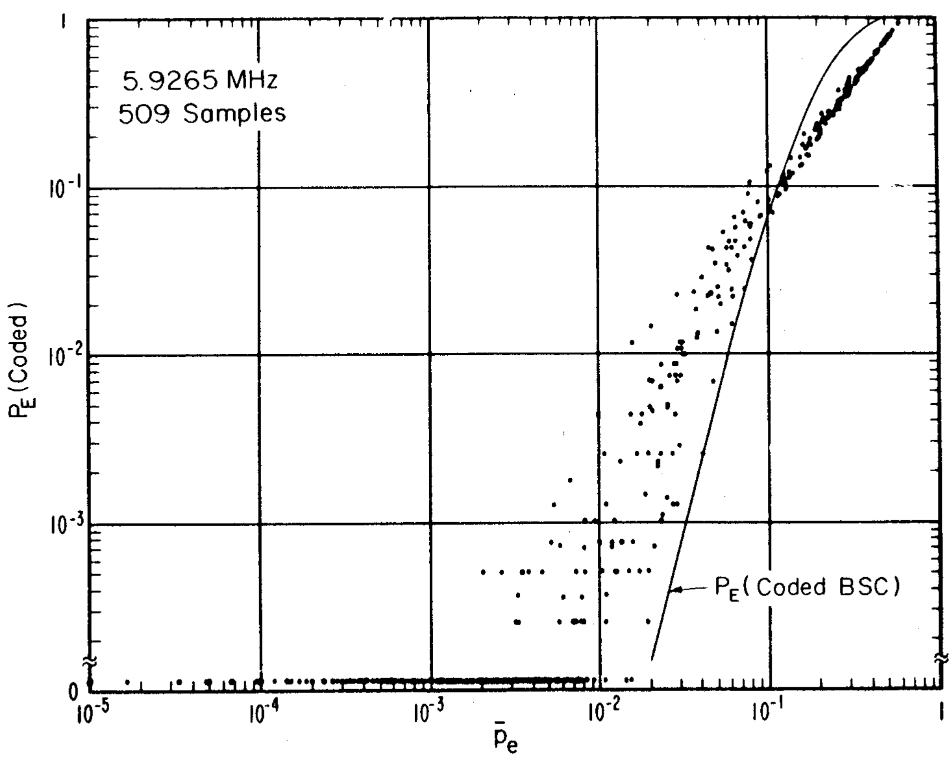


Fig. 9 - Word Error Probability for a Decoded 15 Bit TTY Codeword During the 5.9265 MHz HF Measurements

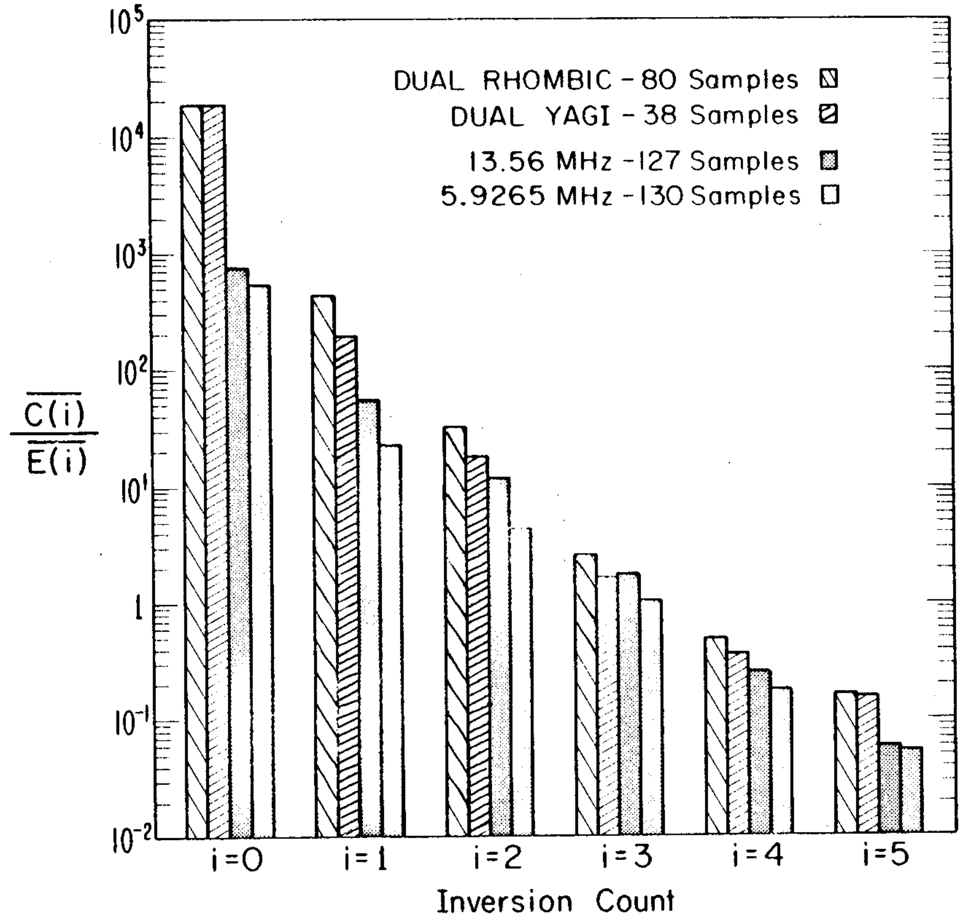


Fig. 10 - Ratio of Characters Decoded Correctly to Characters Decoded Incorrectly Versus Inversion Count