COMMUNICATION CHANNEL CHARACTERISTICS AND BEHAVIOUR OF INTRABUILDING POWER DISTRIBUTION CIRCUITS

by

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ABSTRACT

Intrabuilding power distribution circuits offer a number of unique advantages for local area networking. To enable the selection of proper error-control codes and protocols for reliable data communication services, error pattern statistics of intrabuilding power line channels are obtained. Also, error-causing disturbances are identified and their relationships to specific types of error patterns are determined. It is found that error occurrence is highly periodic, with periodicity being a function of the power line frequency which is nominally 60Hz in North America. Furthermore, results indicate that error pattern behaviour is relatively insensitive to communication carrier frequency and modulation schemes.

Based on the measurement results, hybrid ARQ with bit-interleaving is suggested for reliable data transmission at high data rate (19,200bps). Burst error correcting codes can be used to reduce decoder cost and complexity with some sacrifices in performance. At lower data rates (1,200bps or below), effective error control can be accomplished more easily.

Finally, the attenuation characteristics of a number of typical power line channels are presented. It is found that high frequency bypass can be used to improve signal transmission between different phases of the distribution transformer.

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1. INTRODUCTION

1.1 Communication Through Intrabuilding Power Distribution Circuits

The demand for local area networks for office automation, security monitoring, energy management, computer communications and intrabuilding environmental control enjoys ever increasing demand. Installation of communication cables for such purposes may involve substantial installation costs, appearance compromises to building interiors, inconvenience or limitations on equipment locations. Radio or infra-red links are potential alternatives; however, radio implies licensing and interference, while infra-red requires line-of-sight transmission.

Another alternative is to utilize a channel which is already available, namely the intrabuilding electric power distribution network [1-2]. This network is almost universal in coverage and is easily interfaced using a standard wall plug and outlet socket. Power line channels do suffer from frequency selective attenuation, relatively high noise level, and varying levels of impedance, noise and attenuation [2-4].

Appropriate error control is needed for operation on any data channel to provide high reliability. In particular, forward error correction (FEC) coding or error detection and retransmission are the most commonly used methods to achieve such improvement. Both error correction and retransmission imply the use of error control codes; however, the selection of an efficient and reliable code requires detailed knowledge of channel error statistics. This thesis describes extensive measurements and analysis of channel error statistics for a number of intrabuilding power line channels. Statistics obtained include burst length as well as inter-burst (error-free) length distributions. Results were obtained at various carrier frequencies (from 60KHz-120KHz) and data rates (from 1,200-38,400bps), with attention focused on high speed transmission (19,200bps or above). In addition, the error-causing disturbances are identified and their effects on error pattern behaviour are determined. Narrow-band (FSK, PSK) signalling as well as wide-band signalling (DS/SSMA-FSK, DS/SSMA-PSK) schemes were used in the tests. The measurements were performed at various days and time periods, reflecting different levels of electrical activities on the channels.

Attenuation, noise and impedance are among the most fundamental characteristics of any communication channel, including power line circuits. These basic channel factors are always the subjects of extensive study as a good understanding of them is desirable. Recent studies [3-4] have revealed the behaviour of noise and impedance found on residential power distribution circuit; however, detailed measurements on the attenuation aspect of power line channel are currently unavailable. Thus, the attenuation characteristic as a function of frequency for various types of power line channels were examined and compared. Effects of some common household appliances on signal transmission through power line channels were also considered. The results obtained can be used in the effective design of communication systems involving the use of intrabuilding power line channels.

1.2 Review of Previous Work

1.2.1 Channel Error Statistics

Error control codes with various error handling abilities are readily available in the literatures [5]. However, the choice of an appropriate code is highly dependent upon the form of error patterns encountered, particularly when the code is used for error correction. When FEC coding is employed, the use of a code with excessive redundancy may degrade system throughput, while the use of too little redundancy may increase the bit error rate of the system.

In order to choose appropriate codes for error control, detailed knowledge of channel error statistics is required, including burst error length as well as inter-burst length distributions. Some field measurements of error patterns on transequatorial HF radio links [6], and on urban land mobile radio channels at the 463MHz band [7] are available, and similar results exist for simulated VHF, UHF urban land mobile radio channels at the 800MHz band [8-9]. However, there have been no reports of error pattern statistics for intrabuilding power line channels.

1.2.2 Signal Attenuation Characteristics

Signal attenuation is one of the fundamental characteristics of any communication channel. With this and other knowledge, such as channel noise and impedance levels, one can estimate the amount of transmitter power needed to achieve a specific level of performance (average bit error rate). Such knowledge also enables efficient utilization of the frequency spectrum.

Recently, Vines and others [3-4] measured the noise and impedance levels of residential power distribution circuits. A survey of power line noise levels at a number of other locations, ranging from an urban business office to a rural farm, was reported by Smith [10]. Impedance measurements on power distribution systems throughout the United States and European countries were reported in [11-12]. However, very little previous work has been done to reveal the transmission characteristics of intrabuilding power line channels. Oschner [2] had reported some results in this regard; nevertheless, extensive results other than those presented in this thesis are not available.

1.3 Scope of the Thesis

In chapter 2, the definition of burst errors is presented, followed by a description of the overall error statistics measurement system. Results of a FSK system operated in an industrial building and an apartment complex are then given, for various data rates and carrier frequencies.

In chapter 3, statistics of error patterns obtained using a PSK system are presented. The results are compared with those obtained using the FSK system. The general probability of error performance of systems in the presence of impulse noise (which is a dominant cause of errors in power line channels) is discussed.

In chapter 4, a DS/SSMA-FSK and a DS/SSMA-PSK system are described. Statistics of error patterns obtained using the two systems are presented.

In chapter 5, various error control schemes are considered, on the basis of the measurement results and observations. Suggestions for the selection of error-correcting codes and design of error control protocols are given. The overall design philosophy is then described.

In chapter 6, the transmission characteristics of a number of typical power line channels are investigated. The effects of some common household appliances on signal transmission are presented.

Conclusions and suggestions for future work appear in chapter 7.

2. CHANNEL ERROR STATISTICS FOR A FSK SYSTEM

Error statistics measurements for intrabuilding power line channels were carried out on actual power distribution circuits. An industrial building having a large variety of loads, including industrial machinery, power factor correction and motor starter capacitors, computers and specialized equipment, was chosen. Tests were also done at a residential complex which has approximately 50 apartment units.

Results were obtained at various data rates (1,200-19,200bps), carrier frequencies (60-120KHz) and time periods, with the average bit error rate (BER) as the parameter. Situations where the transmitter and receiver were placed on the same phase of a step down transformer, and on different phases (legs) of a step down transformer have been studied.

2.1 Burst Error Definition

A typical error pattern is shown in Fig. 2.1. A "0" denotes a correct bit, an "e" denotes an error bit.

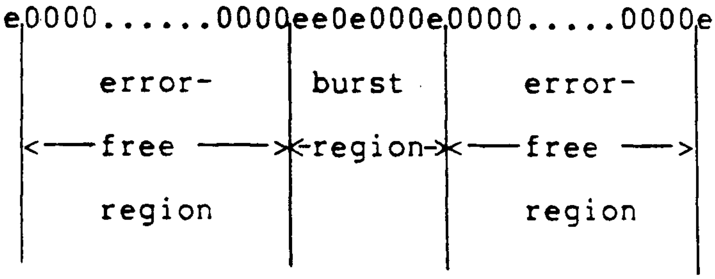


Fig. 2.1 Definition of Burst Error

Following [8-9], a burst region begins and ends with an error bit. A burst region may contain some correct bits whose run lengths are less than a specified value. On the other hand, an inter-burst (error-free) region consists of consecutive correct bits whose run length is equal to or greater than the specified value. A burst region is always preceded and followed by an error-free region and vice versa. The specified value used in the error statistics measurements was 50 bits.

2.2 The Measurement System

The error statistics measurements were carried out with the measurement setup shown in Fig. 2.2. The data source is a pseudorandom binary sequence (PRBS) generator with period equal to $2^{11}-1$. The coupling network is a passive high pass filter used to block the 60Hz power voltage. The recovered data from the receiver output is compared with the locally generated reference data to obtain the error patterns.

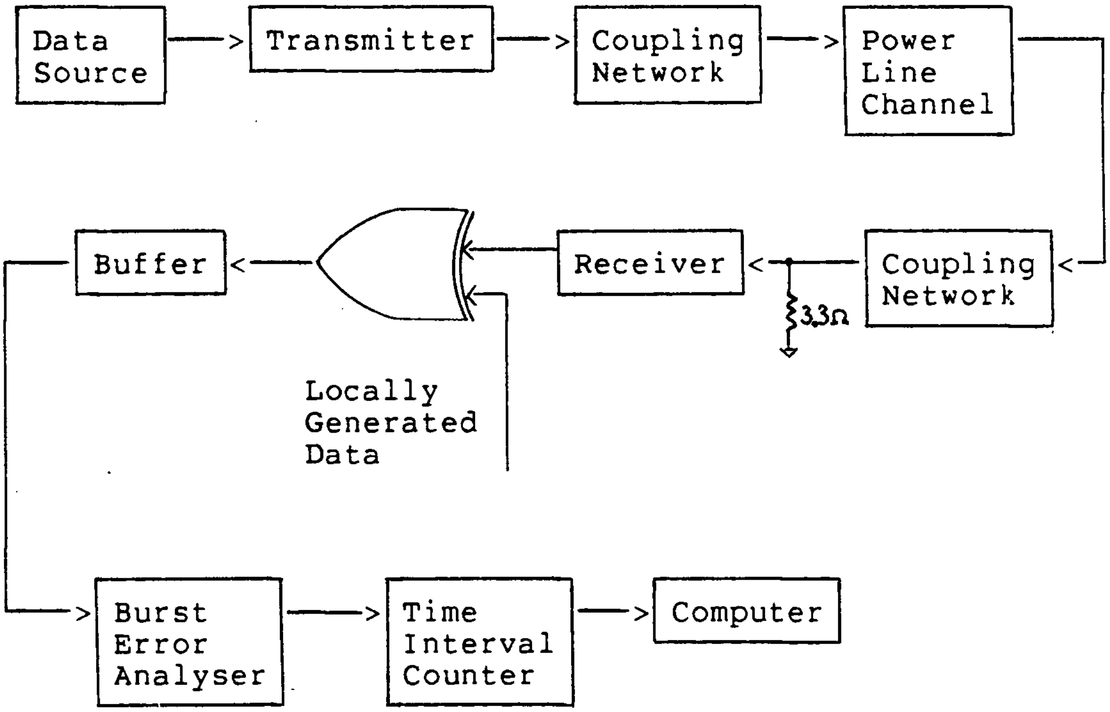


Fig. 2.2 Error statistics measurement system

The error patterns are buffered in order to eliminate possible glitches produced as a result of the exclusive-or operation. The buffered error patterns are then fed into the burst error analyser which produces pulses whose widths correspond to the length of error bursts as defined in Section 2.1. At the same time, inter-pulse width corresponds to the length of the error-free region. The outputs of the burst error analyser are measured by a time-interval counter, and the results are logged into a personal computer, statistically processed and plotted.

2.2.1 The Burst Error Analyser

The burst error analyser is adopted from [8-9] and shown in Fig. 2.3.

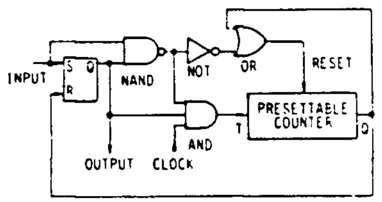


Fig. 2.3 Burst error analyser [8-9]

The analyser monitors the error patterns for the above mentioned specified error-free lengths. This specified error-free length is the value set in the presettable counter. Error bursts as defined in Section 2.1 are detected and pulse widths proportional to the length of the error bursts are produced. Detailed descriptions of the operation of the burst error analyser can be found in [8]. Predetermined error patterns were used to verify proper operation of the overall measurement system.

2.2.2 The Transmitter and Receiver

The transmitter is a FSK modulator with frequency off-set $\pm\Delta f$ equal to 1/4 of the data rate; this corresponds to the MSK modulation condition [26-27] for that particular data rate. The centre frequencies used in the tests were 60KHz and 120KHz.

The receiver consisted of a coherent FSK demodultor preceeded by band pass filter for noise suppression. The band pass filter has a 3-dB down bandwidth of about 40KHz centered around the center frequency.

Tests of the modem in the presence of additive white gaussian noise confirms proper functioning of the modem hardware.

2.3 Measurement Results: Industrial Building

Extensive measurements were made on an industrial building having a large variety of loads, such as industrial machinery, power factor correction and motor starter capacitors, computers, and other loads. This building represents a very hostile environment for power line communications. In large buildings in North America including our test building, three-phase power is sent directly from a three-phase distribution transformer to circuit panels inside the building from where branch circuits carry power to desired locations. Placement of the transmitter and receiver on the same phase of the step down transformer will hereinafter be referred to as "in phase" signal transmission, while placement of the transmitter and receiver on different phases of the step down transformer will hereinafter be referred to as "across phase" transmission. The transmitter power was adjusted to obtain average bit error rates in the critical range between 10^{-2} and 10^{-4}. The results presented were selected from the large number of available experiments to show both typical and rare error-causing disturbances that affect power line communications.

2.3.1 Channel Error Statistics: 19,200bps Data Rate, 120KHz Carrier Frequency

The cumulative distribution of burst error length obtained during typical in phase signal transmission is shown in Fig. 2.4. It is observed that single bit errors occupy a

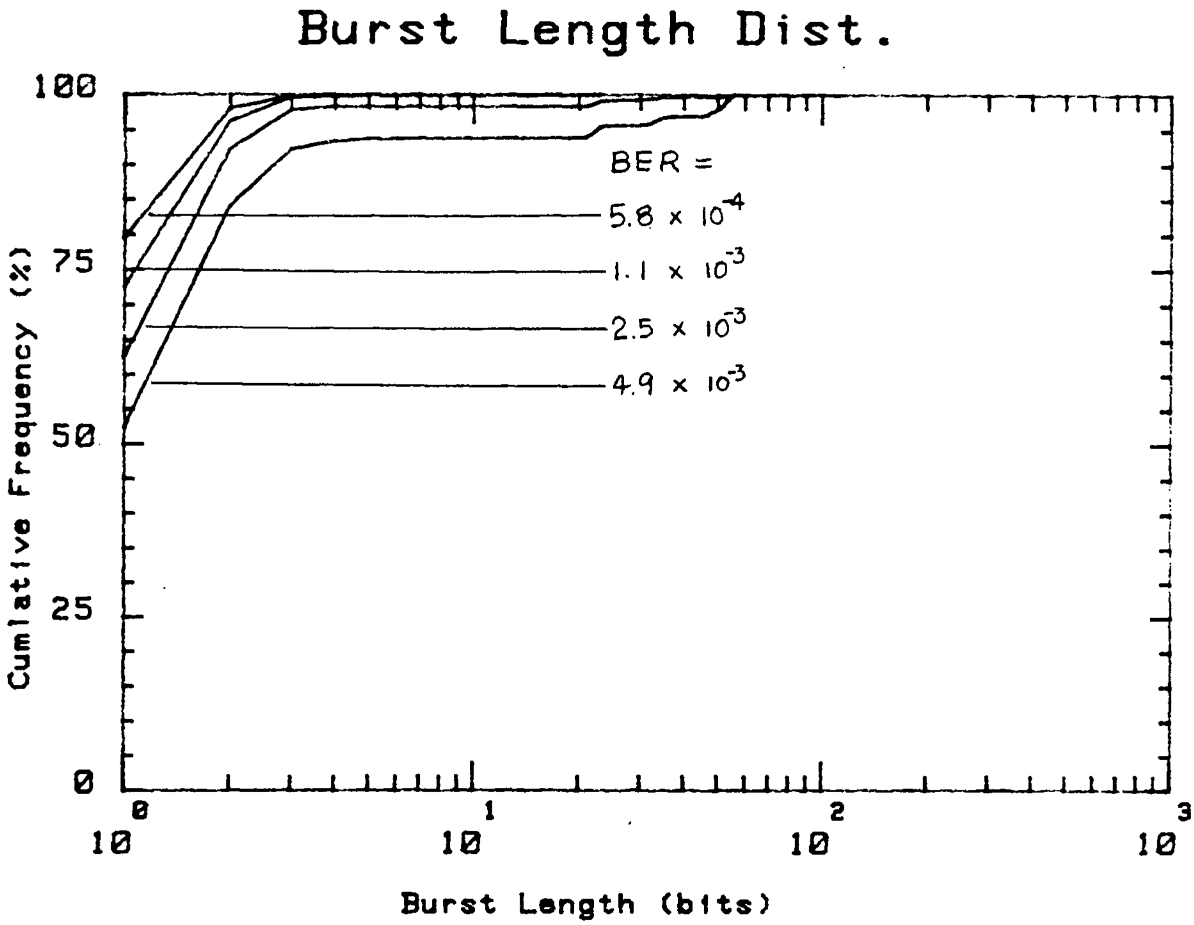


Fig. 2.4 Representative burst error distribution. FSK: 19,200bps data rate, 120KHz carrier frequency. In-phase transmission.

large percentage of the errors and burst errors composed of only a few bits predominate in the total error occurrence. The cumulative distribution of error-free length is shown in Fig. 2.5. Fig. 2.5 shows that the percentage of long error-free lengths is large. It is also observed that there are many discrete jumps in the curves, which means that there are high relative frequencies of some specific error-free lengths. This phenomenon suggests that error occurrence is mostly periodic. In other words, error occurrence must be somehow synchronous or correlated with the periodic 60Hz power line voltage.

Periodic error effects can be seen from Fig. 2.6 and 2.7. In Fig. 2.6, the upper trace is the 60Hz power line voltage; the lower trace is the power line noise, after the receiver's band pass filter. The noise pattern, particularly the high-level impulse noise spikes, is seen to be correlated with the periodic 60Hz power voltage. In fact, the noise-level pattern tends to repeat itself every half power cycle. This observation of power line noise generally agrees with those reported in [3].

In Fig. 2.7, the upper trace is the received signal plus noise, after the receiver's band pass filter; the lower trace is the error pattern. As one can see from the figure, a lot

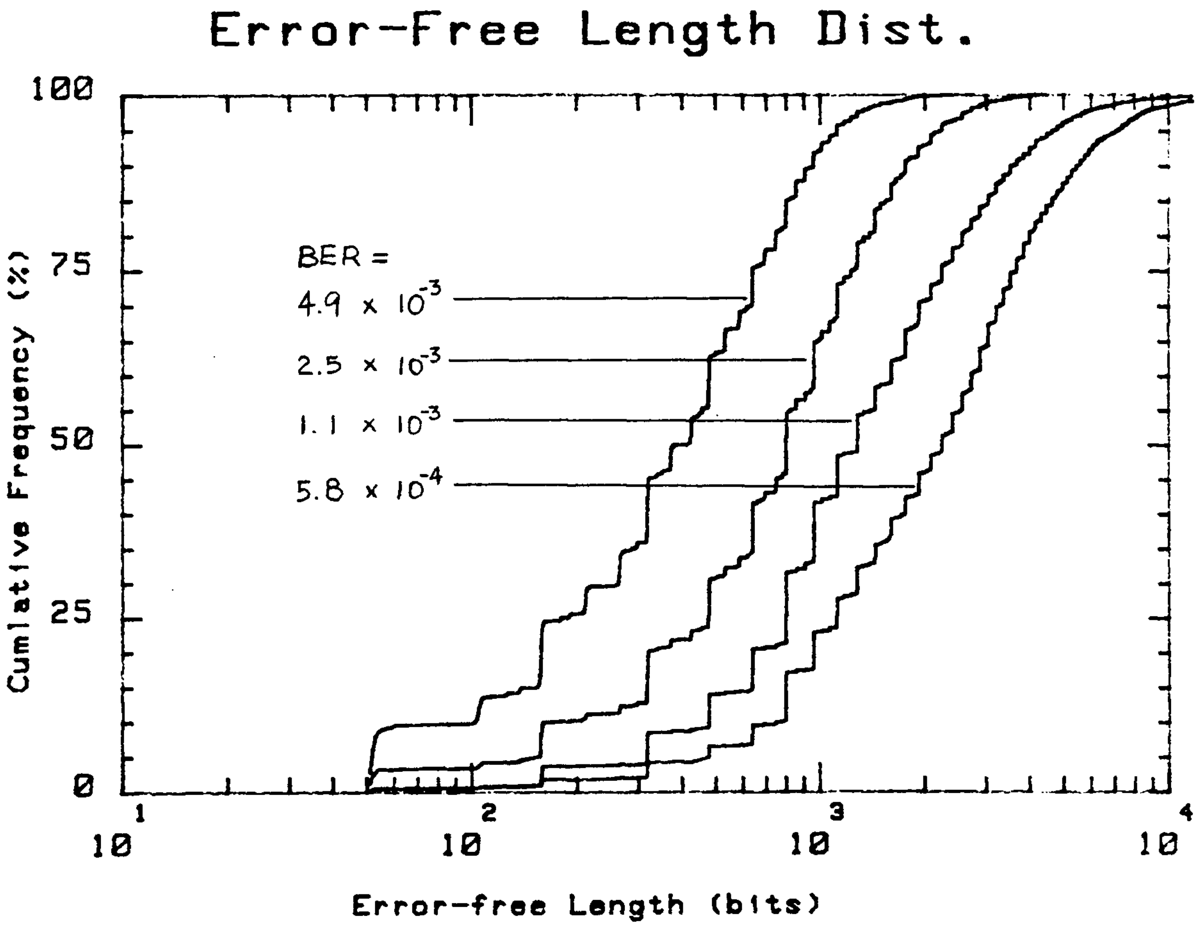


Fig. 2.5 Representative error-free length distribution. FSK: 19,200bps data rate, 120KHz carrier frequency. In-phase transmission.

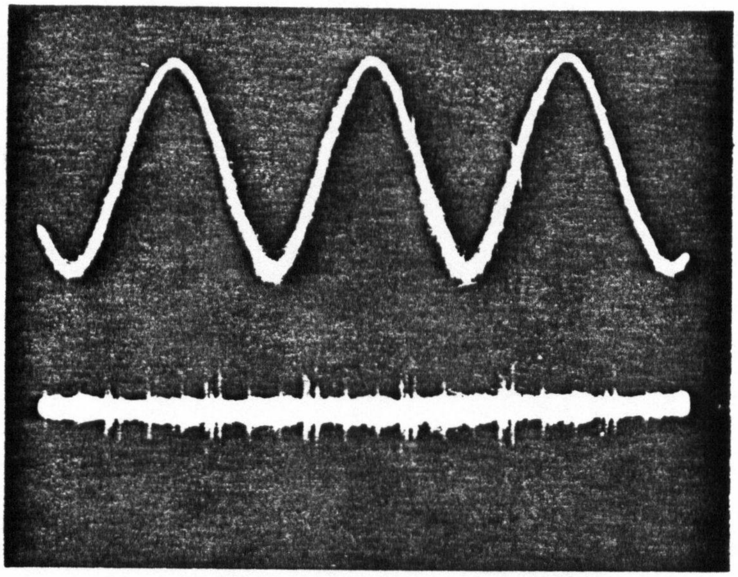


Fig. 2.6 Power line noise.

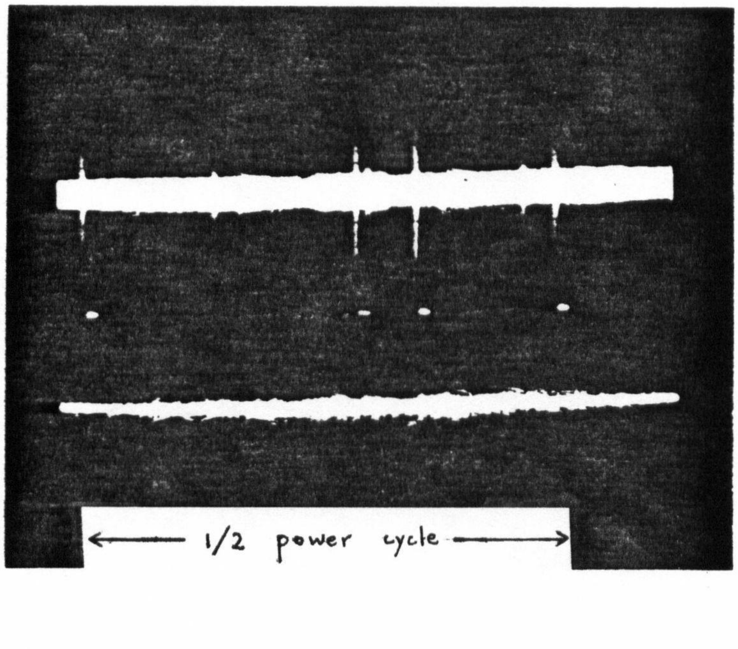


Fig. 2.7 Observed error pattern.

of errors occur during the presence of impulse noise spikes and these errors are correlated with the periodic 60Hz power line voltage as are the impulse noise spikes. The received signal level shown in the picture was well above the average background noise level. This extra received power is needed in order to combat impulse noise disturbances. Such a received signal level would enable virtually error-free data transmission if the high level noise impulses were absent. Clearly, power line communications are very vulnerable to impulse noise.

Impulse noise effects can be understood more clearly with the results shown in Fig. 2.8 which were obtained during the period when very strong and stationary periodic impulse noise occurred. The noise pattern was similar to that shown in Fig. 2.9, i.e. one hugh noise spike every half power cycle. The time interval between the noise spikes was 1/120 second which was equivalent to 160 information bits for a 19,200bps data rate system. Since virtually all errors found under this channel condition were caused by the hugh impulse noise spikes, the time intervals between the error bursts should be around n x 1/120 second, where n=1,2,3,......, depending whether or not successive impulse spikes caused errors. In other words, the error-free length should be 160

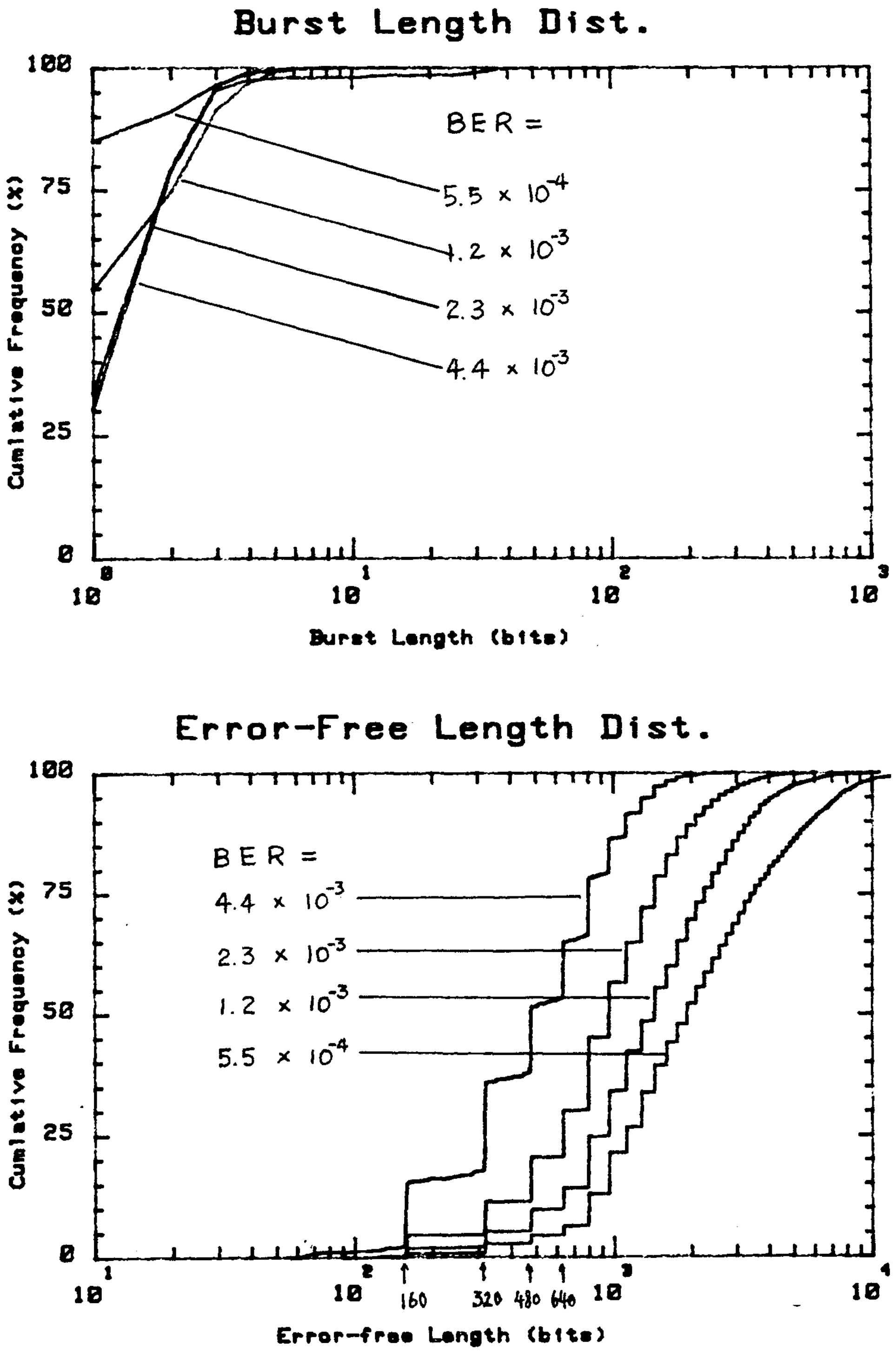


Fig. 2.8 Channel error statistics under very strong and stationary impulse noise impairment. FSK: 19,200bps data rate, 120KHz carrier frequency. In-phase transmission.

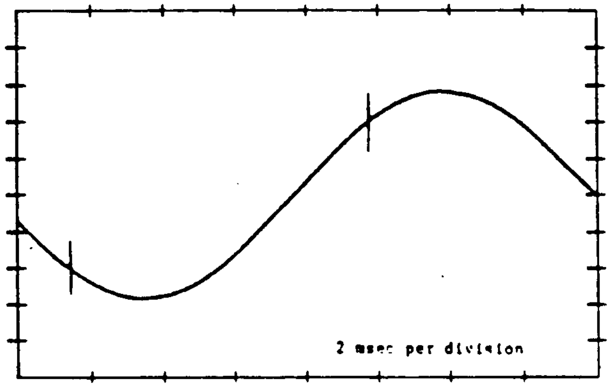
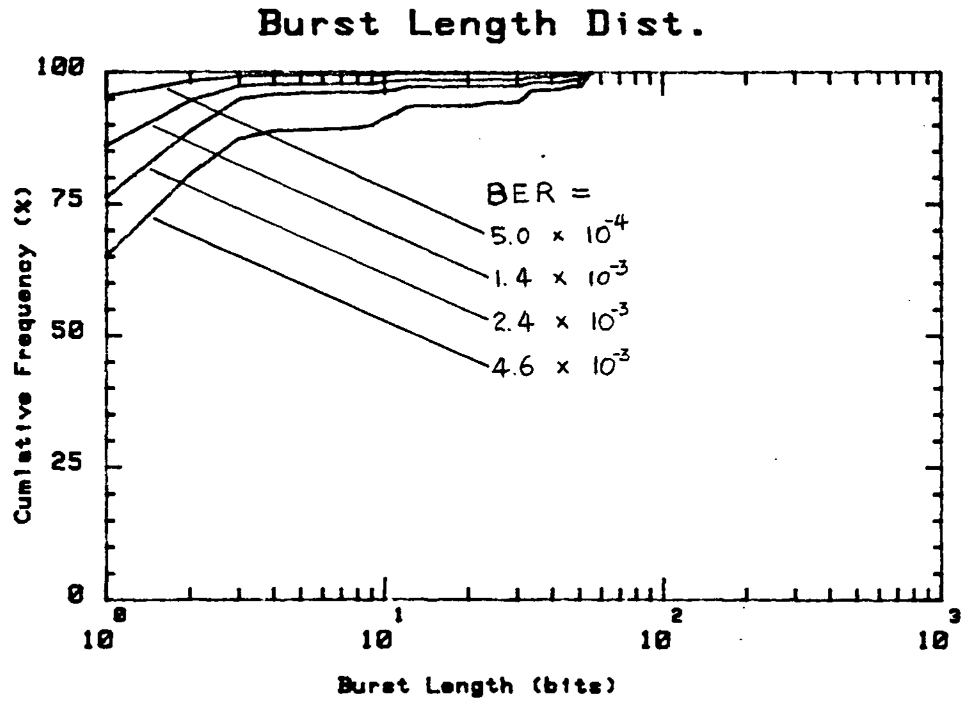


Fig. 2.9 Periodic impulse noise [3].

bits or multiple of 160 bits minus the burst length. This argument is clearly confirmed by the staircase-liked curves shown in Fig. 2.8, where each step jumps at the predicted locations. Power line circuits are the first and only communication channels found to give errors with such high degree of periodicity.

Typical results on the distributions of burst error length and error-free length for across phase signal transmission are shown in Fig. 2.10, 2.11. The results given here are for 2 different across phase signal transmission paths (phase A-phase B phase A-phase C). In both cases, the transmitter remained fixed (at phase A), and the receiver was moved to avoid bias of the results by the environment of a single receiver site. Fig. 2.10 and 2.11 show that burst errors composed of only a few bits predominate the total error occurrence and that the percent of single bit errors increases as BER decreases.

The above results indicate that under typical channel conditions, no significant difference for error pattern behaviour is found between in phase and across phase signal transmission, at the same BER value. This consistency is apparant because impulse noise, the predominant cause of errors, tends to be independent of receiver location and



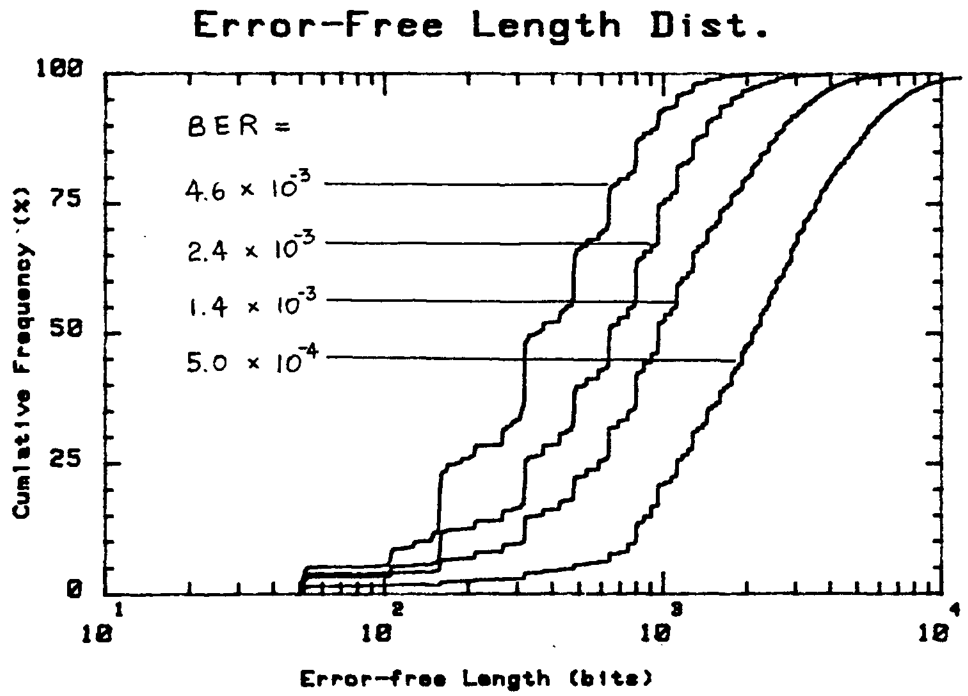
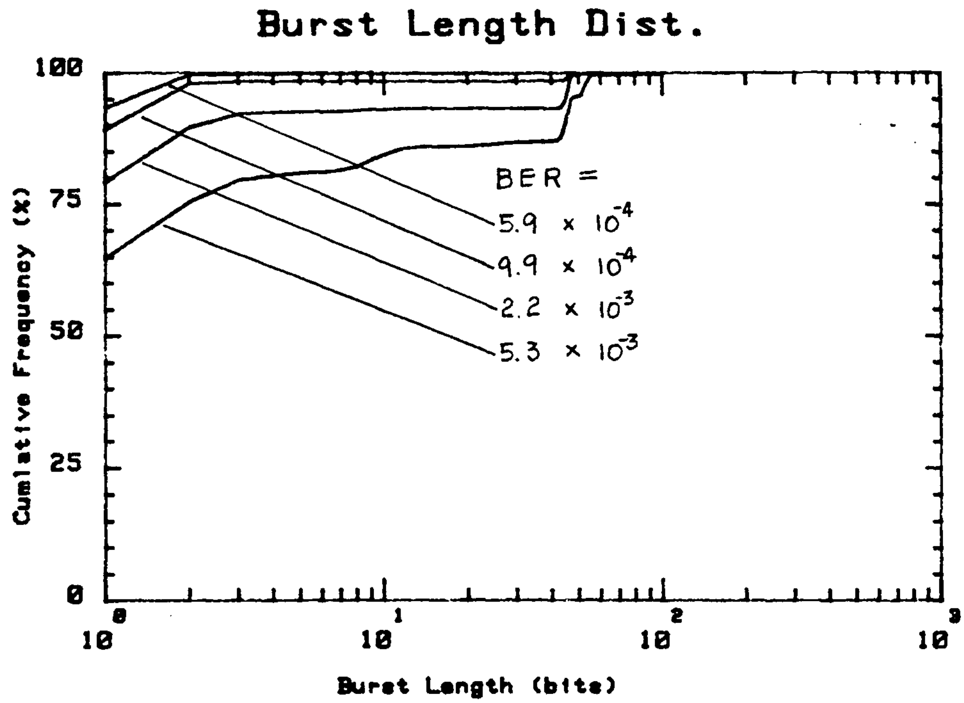


Fig. 2.10 Representative channel error statistics. FSK: 19,200bps data rate, 120KHz carrier frequency. Across-phase transmission.



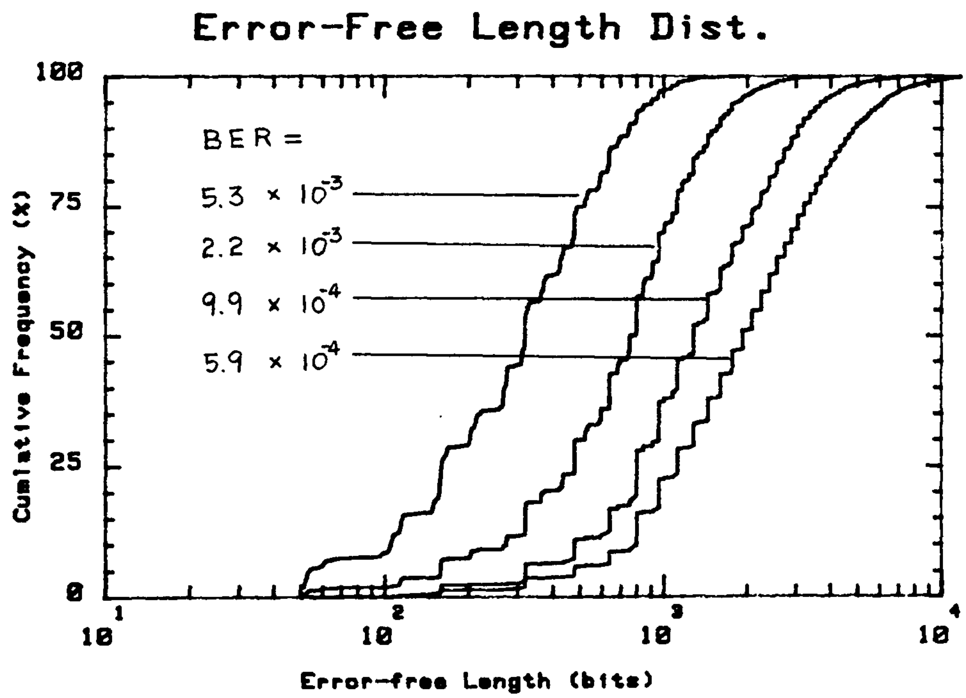


Fig. 2.11 Representative channel error statistics. FSK: 19,200bps data rate, 120KHz carrier frequency. Across-phase transmission.

phase.

However, the performance of across phase signal transmission can be degraded significantly by signal fading impairment. Fig. 2.12 shows the results obtained when the channel was impaired by very severe signal fading occurred periodically at a frequency which is a submultiple of the 60Hz power frequency. Each fade duration lasted about 2-3ms. During the deep fade period, long error bursts occurred. The curves in Fig. 2.12 indicate that error-free lengths of approximately 3,000 bits predominate all other lengths, reflecting the situation that error occurrence concentrated during the periodically happened faded periods, leaving the non-faded periods error free. The actual frequency of occurrence of the fades can be estimated as follows:

Average error-free length ≅ 3,000 bits

Average burst error length < 100 bits

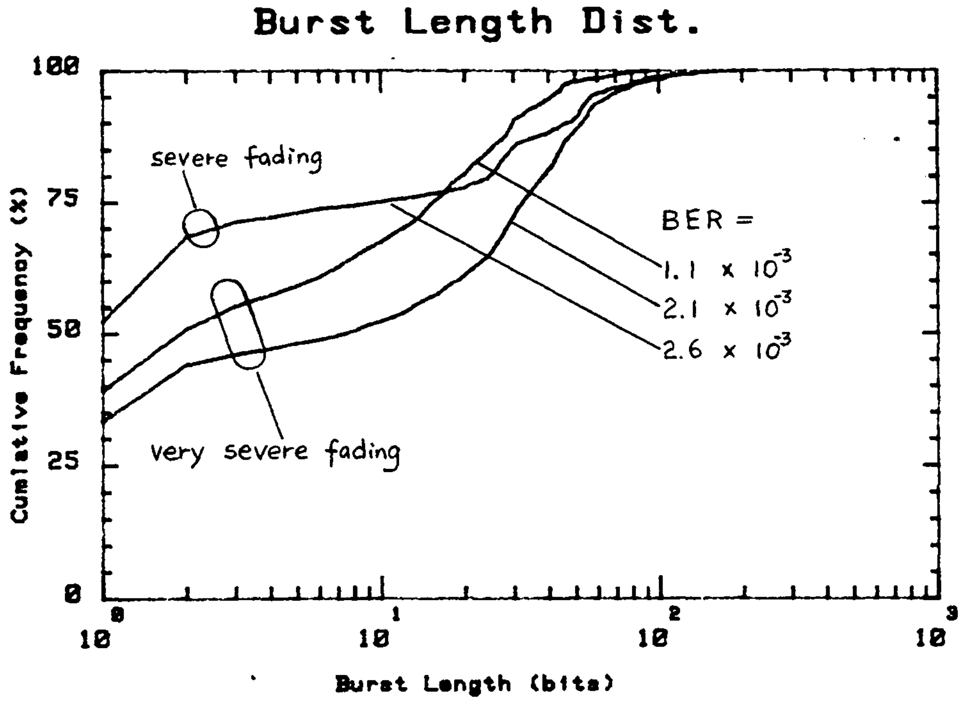
Data rate = 19,200bps

Fading frequency ≅ Data rate/(Average error-free length + Average burst error length)

≅ 19,200/3,100

≅ 6 Hz.

In Fig. 2.13, error distributions are compared for



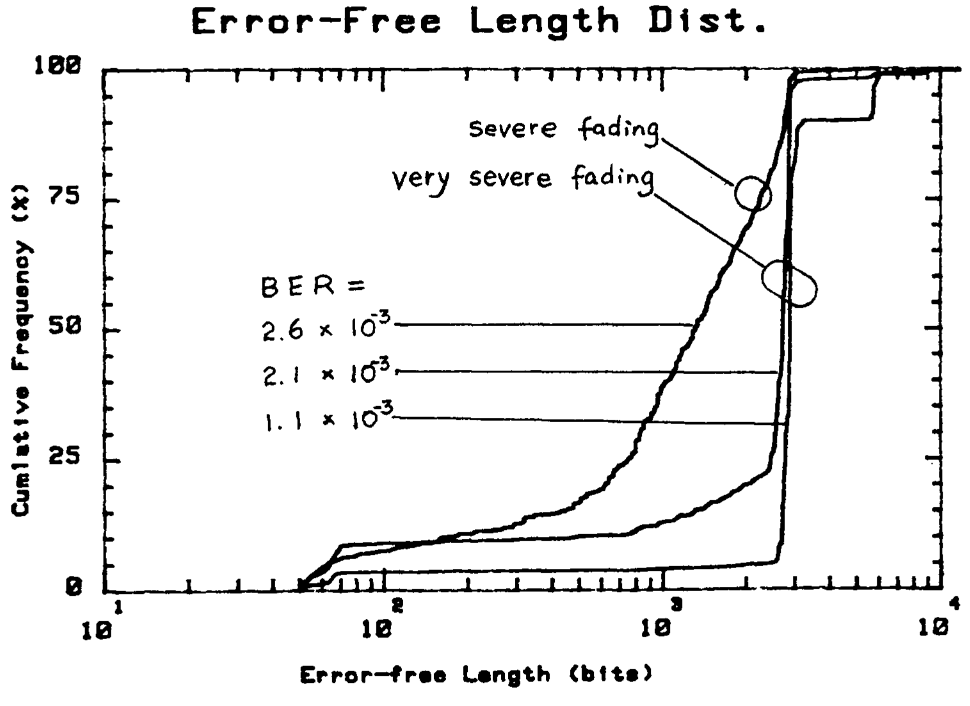


Fig. 2.12 Channel error statistics under severe periodic signal fading at subpowerline frequency. FSK: 19,200bps data rate, 120KHz carrier frequency. Across-phase transmission.

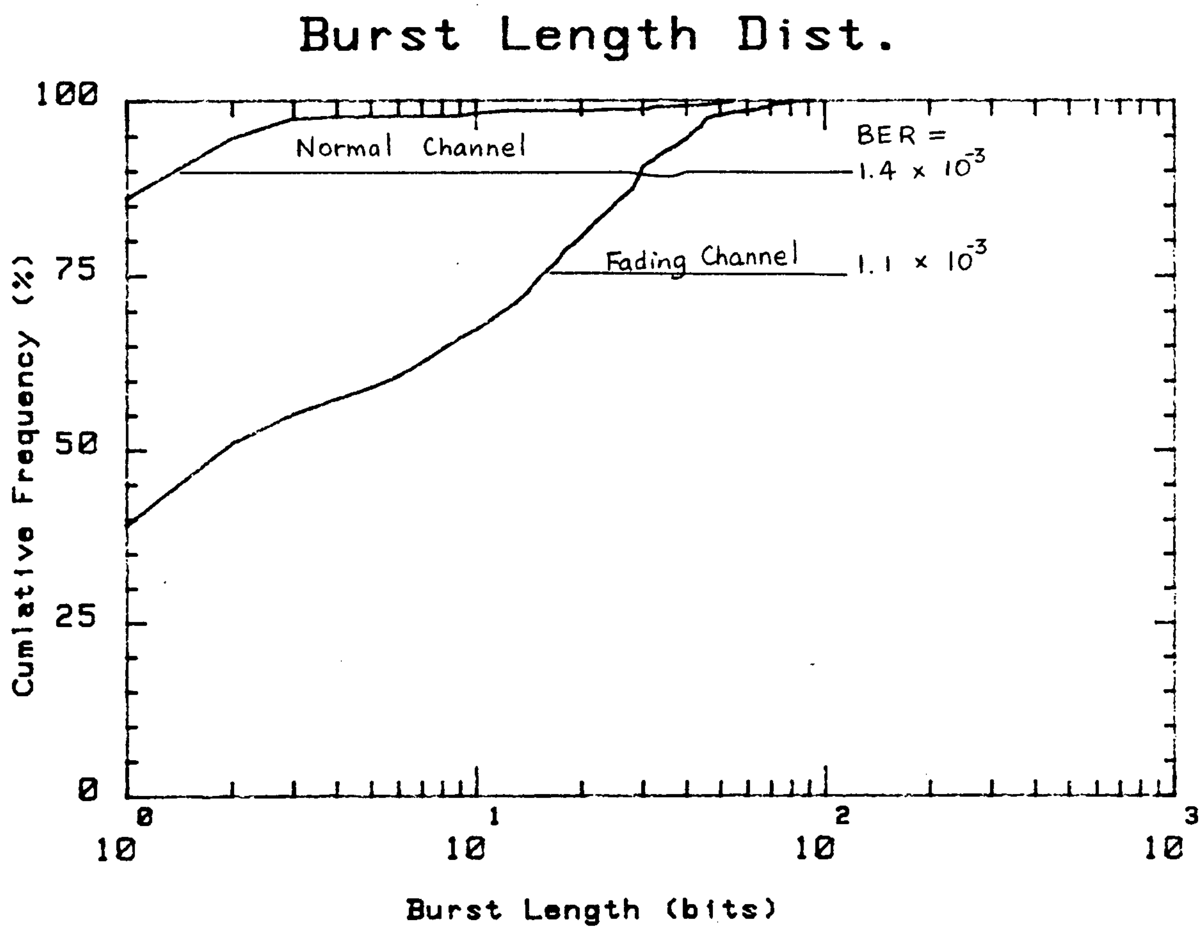


Fig. 2.13 Burst error distribution: Comparison between normal channel and fading channel.

fading and normal channels, with the average BER $\cong 10^{-3}$. The percentage of various burst error lengths is tabulated in Table 2.1. The results confirm that there are many more long burst errors present under signal fading than when fading is absent.

BURST ERROR LENGTH (BITS)	NORMAL CHANNEL (PERCENT)	FADING CHANNEL (PERCENT)
1	86.0674	39.1594
2	8.5724	11.7745
3	2.8352	4.3029
4	.2668	2.1348
5	.0334	1.6678
6	.0000	1.6334
7	.0334	1.9346
8	.0000	1.9346
9	.0334	1.6334
10	.3669	1.1341
Total Percent	98.1988	67.3115

TABLE 2.1 Burst error length percentage: Comparison between normal and fading channel.

This type of time correlated signal fading occurs occasionally. The fade intensity differs each time. However, very severe fading is relatively uncommon and has been observed only during across phase signal transmission.

A second type of periodic signal fading, whose occurrence is also synchronous with the 60Hz power voltage, is much more frequent. Fig. 2.14 illustrates a signal suffering from such an impariment when transmitter and receiver were placed on different phases of the distribution transformer. The upper trace is the 60Hz power line voltage; the lower trace is the received signal envelop of a 115KHz single frequency tone. As observed, the frequency of occurrence of such fading is twice the power voltage frequency.

Deep fades are rarely found in this type of signal fading, but when present can create long error bursts. The effect of deep fades is shown in Fig. 2.15 where the average burst error length plus the average error-free length is approximately 160 bits, i.e., half the power cycle. Again, deep fading has only been observed during across phase signal transmission.

In general, this second type of signal fading itself is seldom strong enough to be the cause of errors. However, in many cases, it makes the system more vulnerable to other types of impairments, particularly those from relatively weak noise impulses. In this regard, it was found to be difficult

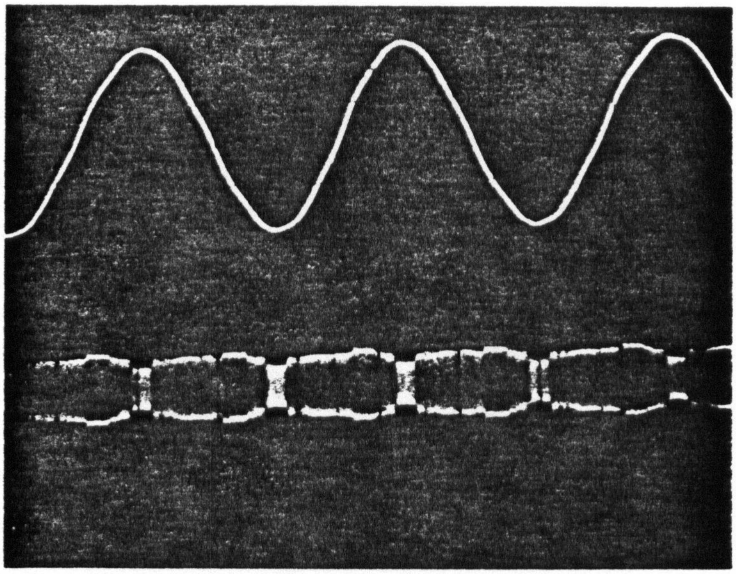


Fig. 2.14 Periodic signal fading at twice the power line voltage frequency.

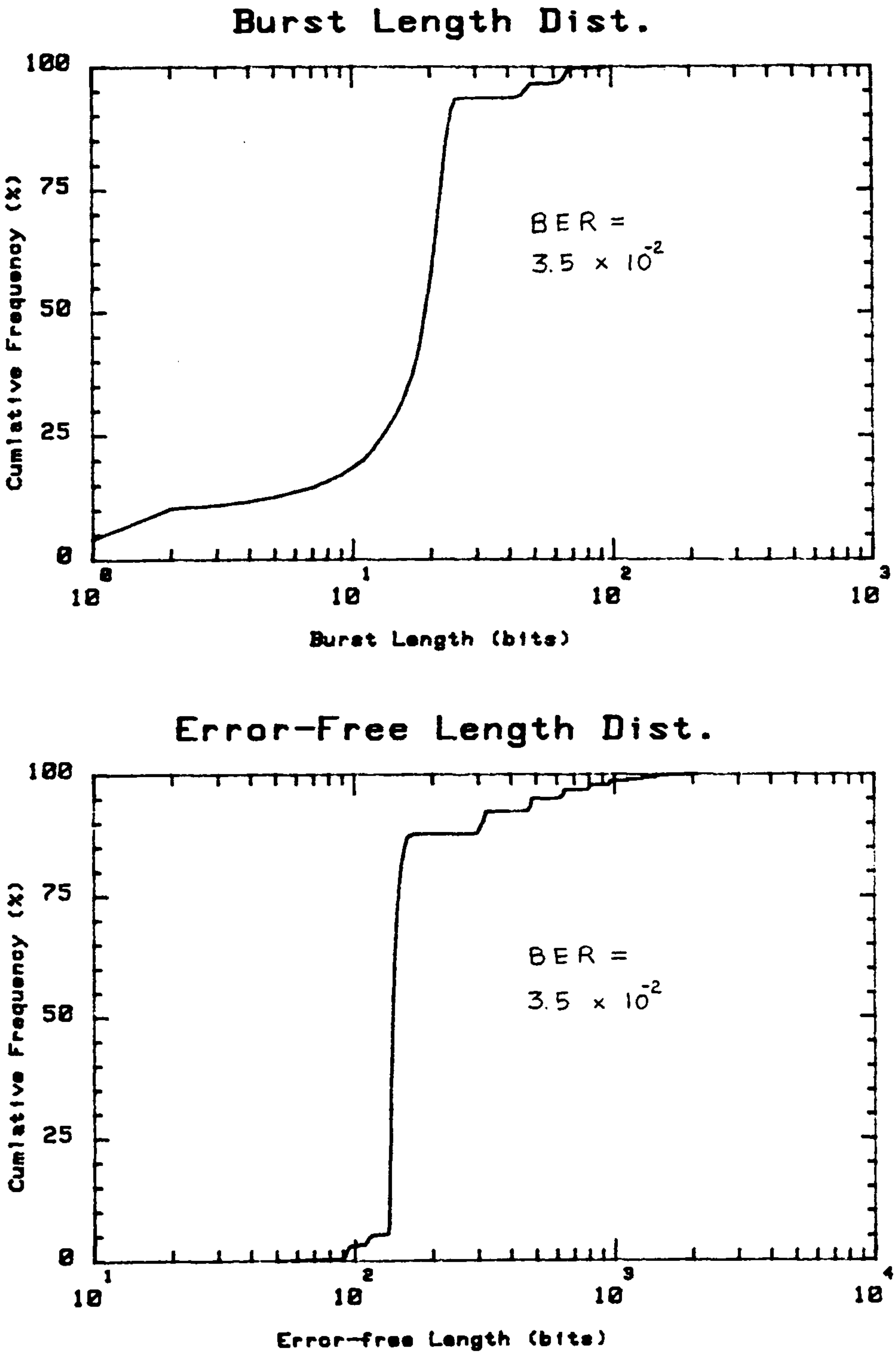


Fig. 2.15 Channel error statistics under severe periodic signal fading at twice the power line voltage frequency. FSK: 19,200bps data rate, 120KHz carrier frequency. Across-phase transmission.

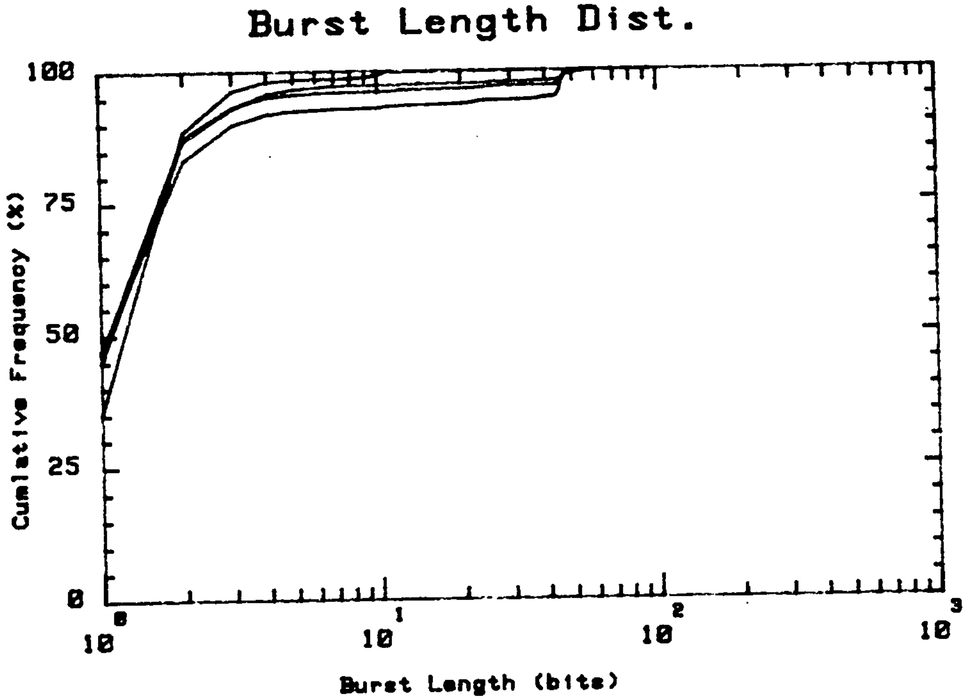
to separate impulse noise and fading effects to determine the exact cause of errors in some of the tests.

Effects on error distributions due to different transmitter-receiver separation distances is shown in Fig. 2.16. Throughout the experiments, the receiver was fixed at the same outlet while the transmitter was placed at outlets located on different floors. The error rate was fixed at 2 x 10 during the tests. The curves show great similarity.

All measurements mentioned so far were recorded on different days and various time periods. Typical transmitter output voltages used (before the coupling network) to obtain the BER range near 10 varied from 1Vrms to 4Vrms during across phase signal transmission. During in phase signal transmittion, the transmitter output voltage used was between 0.5Vrms to 1.5Vrms. In general, more attenuation is encountered during across phase signal transmission (see chapter 6).

2.3.2 Channel Error Statistics: 4,800bps Data Rate, 120KHz Carrier Frequency

The cumulative distributions of burst error length and error-free length for typical in phase and across phase signal transmission are shown in Fig. 2.17-2.18.



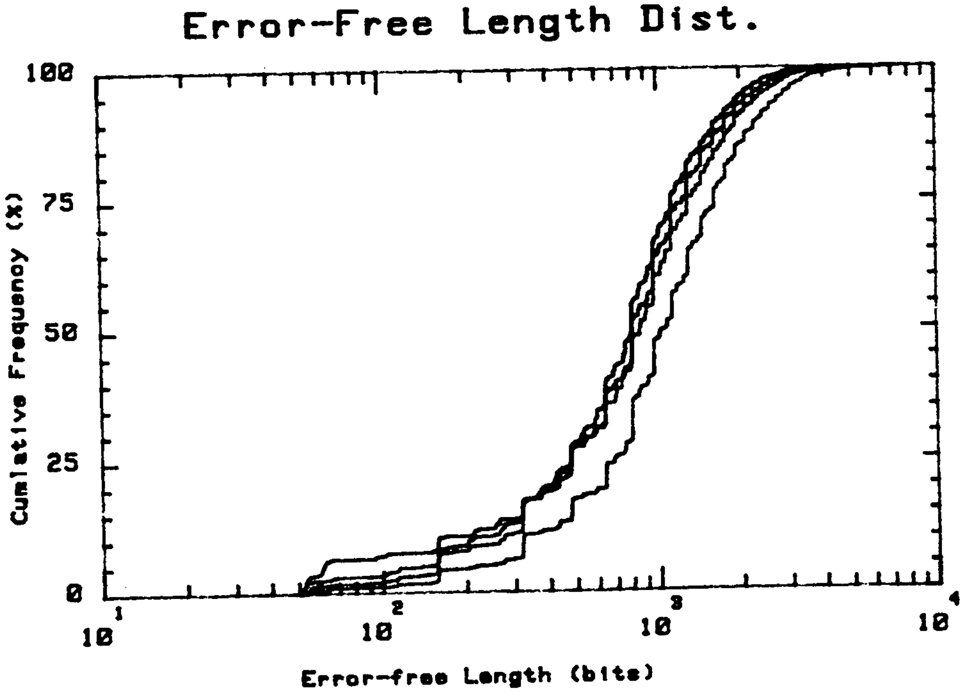
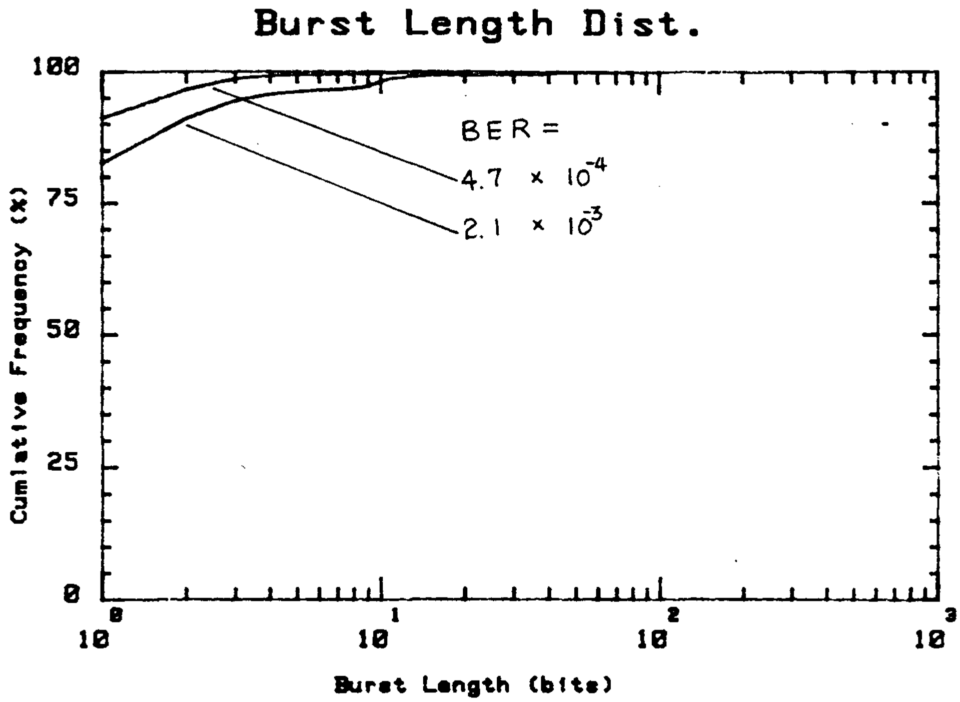


Fig. 2.16 Effect of transceiver separation on channel error statistics. BER = 2×10^{-3} .



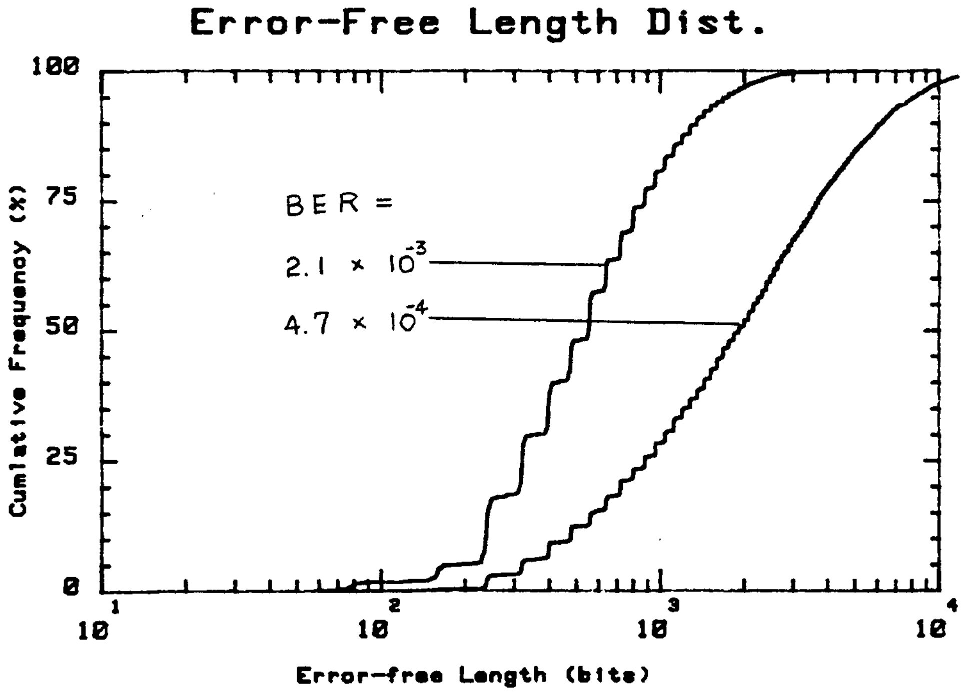
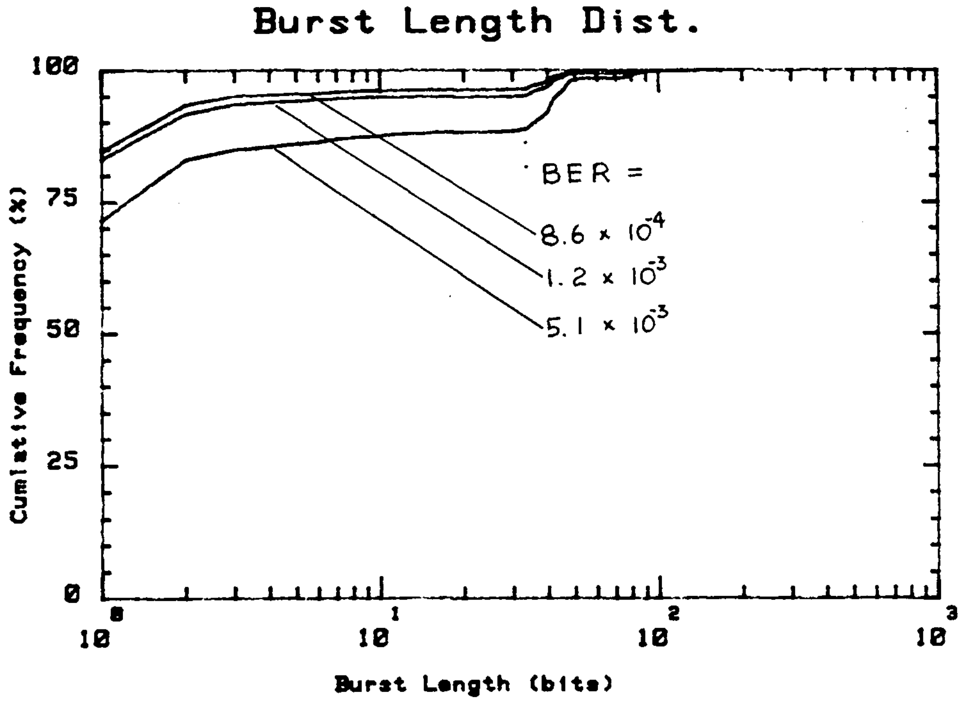


Fig. 2.17 Representative channel error statistics. FSK: 4,800bps data rate, 120KHz carrier frequency. In-phase transmission.



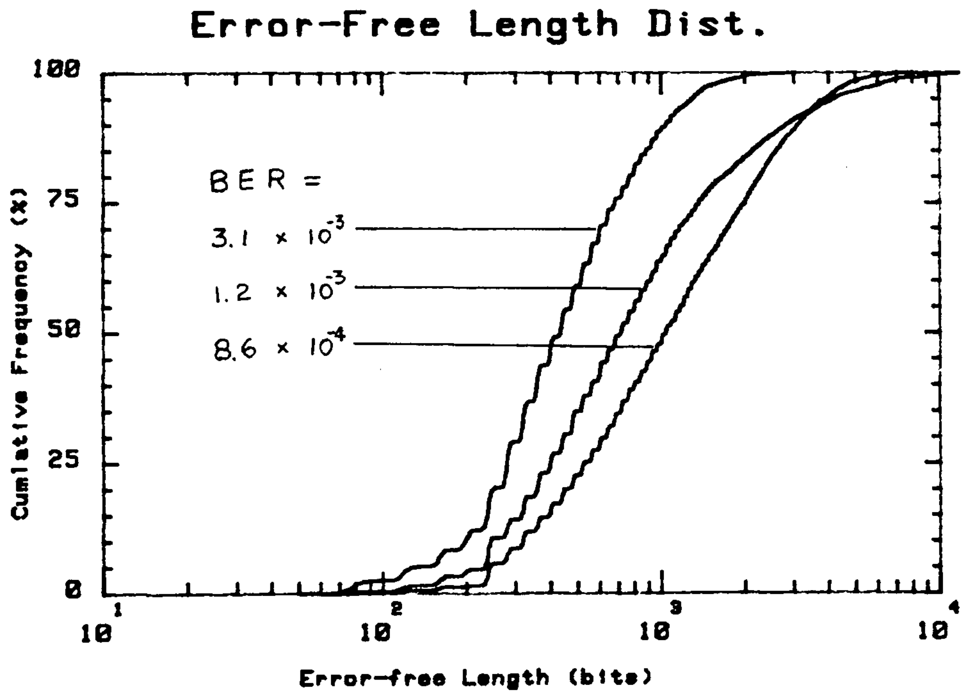
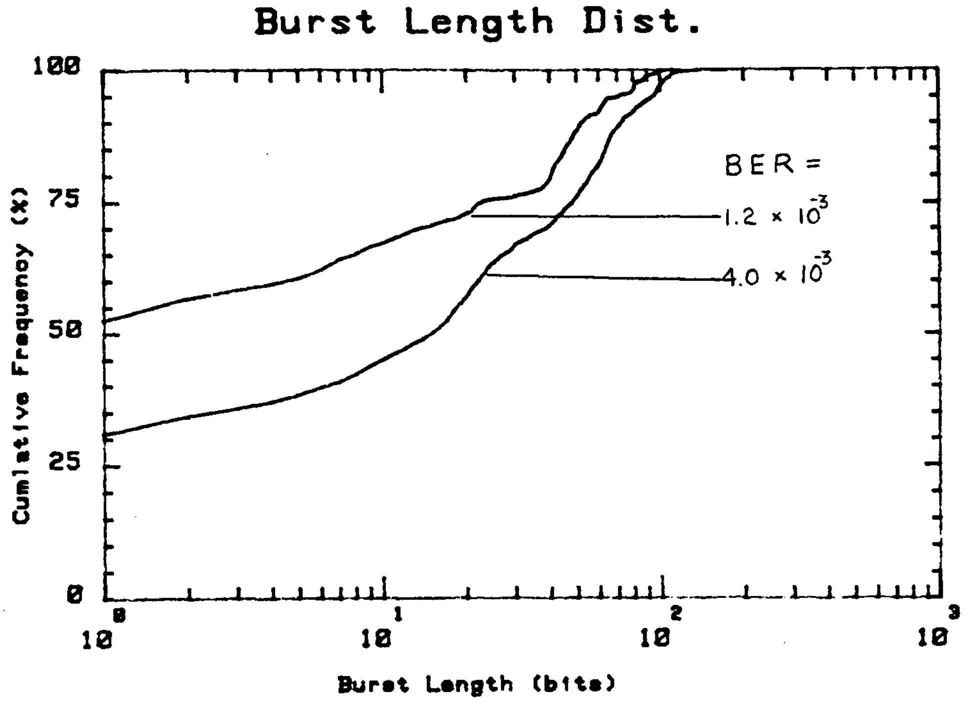


Fig. 2.18 Representative channel error statistics. FSK: 4,800bps data rate, 120KHz carrier frequency. Across-phase transmission.

Impulse noise continues to be the primary cause of errors; however, its effect is less severe because it is more difficult now for an impulse noise spike to obliterate a data bit whose duration exceeds that of the noise spike. Thus, the system requires less received power for combating impulse noise. During the course of the experiments, very severe signal fading similar to that reported in section 2.3.1 occurred in one of the across phase signal transmission paths. The error statistics obtained under such condition is shown in Fig. 2.19. The actual frequency of occurrence of the fading can be estimated to be about 6Hz, by the method similar to that in section 2.3.1. Typical transmitter voltage level used at this data rate was between 100mVrms to 300mVrms.

2.3.3 Channel Error Statistics: 1,200bps Data Rate, 120KHz Carrier Frequency

The cumulative distributions of burst error length and error-free length for typical in phase and across phase signal transmission are shown in Fig. 2.20-2.21. Although impulse noise remains as the major cause of errors, its influence is very much reduced. As a result, at this data rate, the system operates with much lower received power as



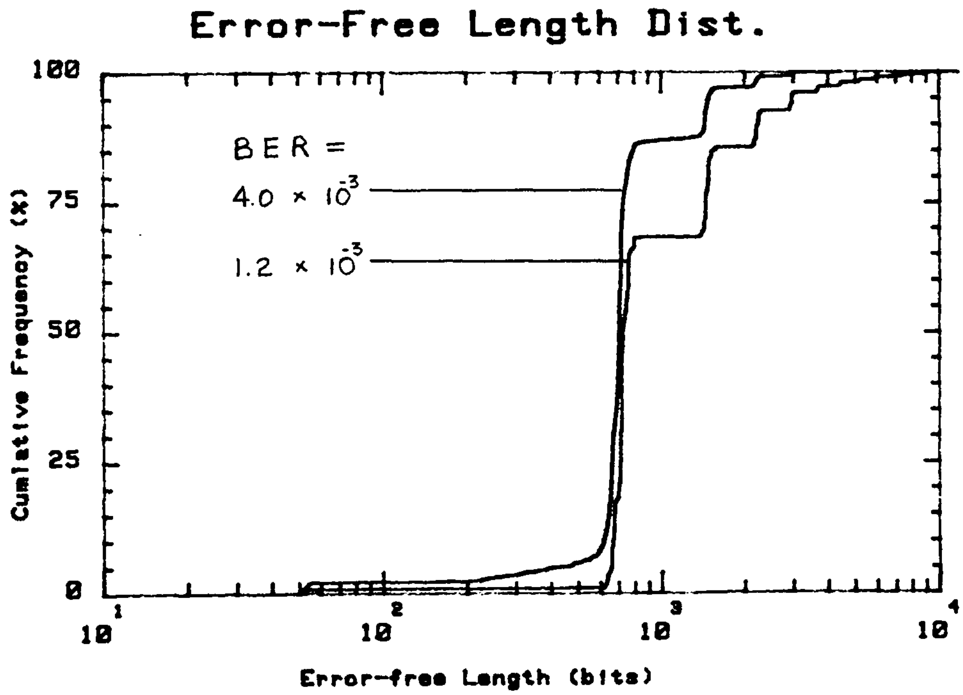
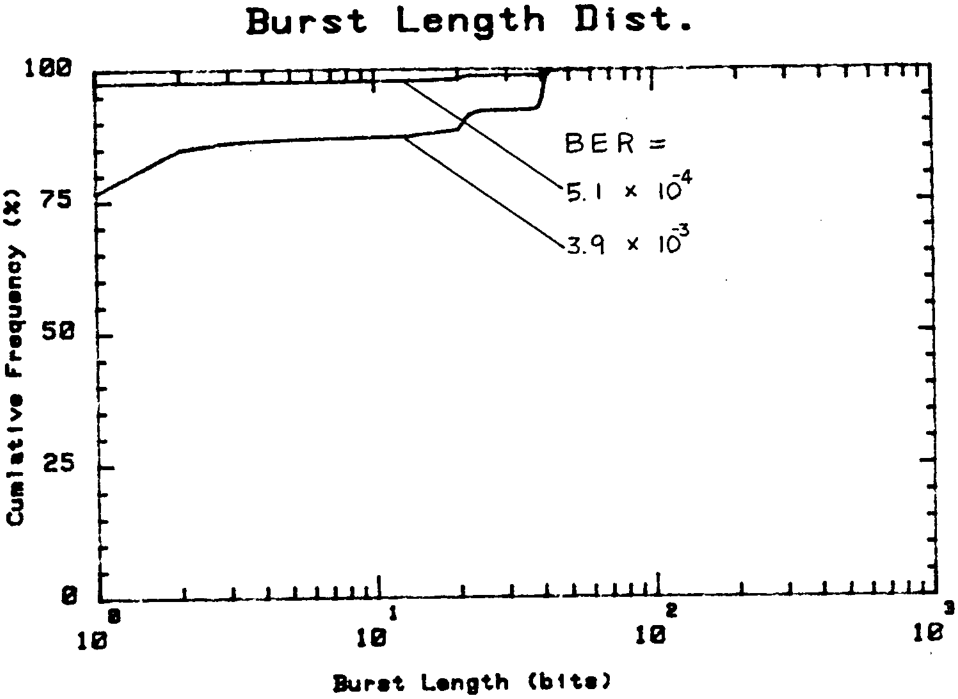


Fig. 2.19 Channel error statistics under severe periodic signal fading at subpowerline frequency. FSK: 4,800bps data rate, 120KHz carrier frequency. Across-phase transmission.



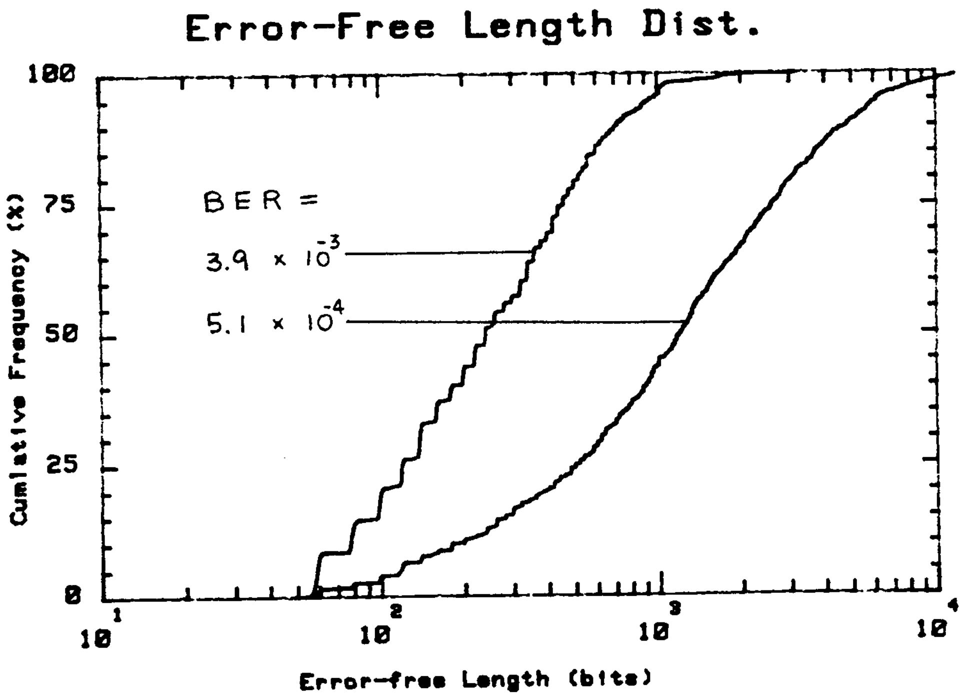
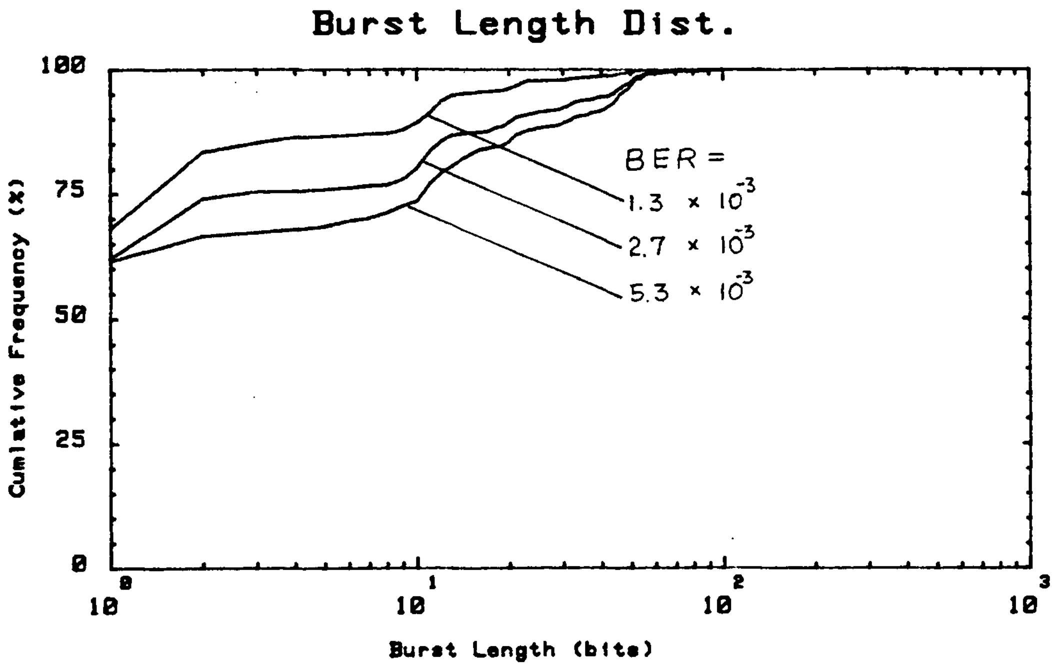


Fig. 2.20 Representative channel error statistics. FSK: 1,200bps data rate, 120KHz carrier frequency. In-phase transmission.



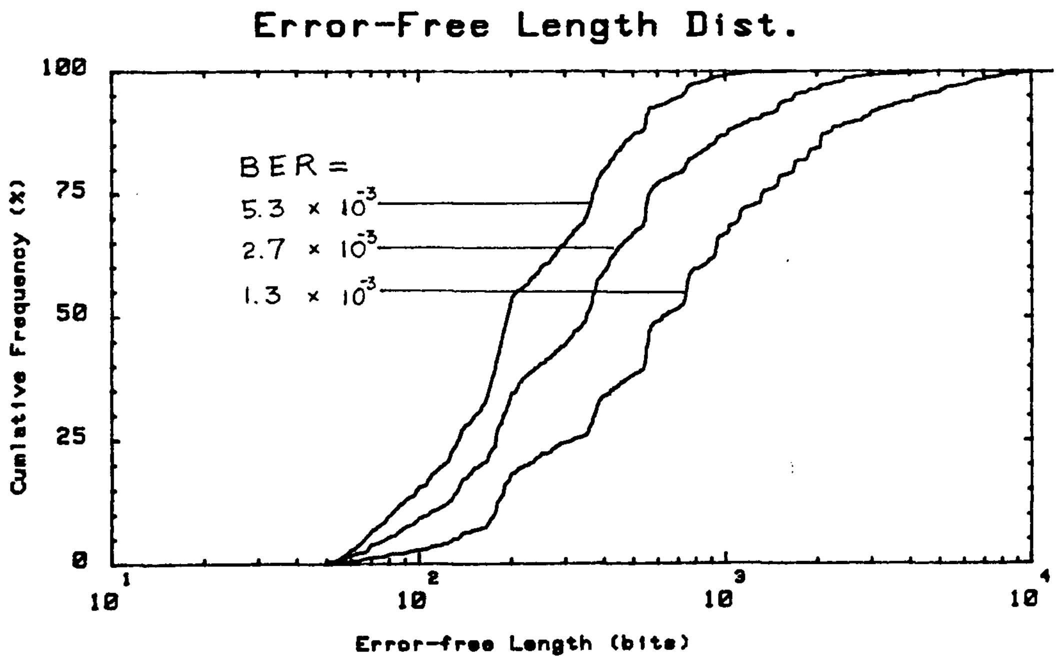


Fig. 2.21 Representative channel error statistics. FSK: 1,200bps data rate, 120KHz carrier frequency. Across-phase transmission.

opposed to the high received power needed by high data rate system, for comparable BER performance. Hence, the system becomes more easily influenced by channel attenuation, fading and background noise disturbance which is non-Gaussian. In fact, the background noise exhibits a periodic pattern at twice the power voltage frequency (see Fig. 2.22). As a result, there can be slightly more burst errors at low signal level. Typical transmitter voltage levels used at this data rate were around 100mVrms.

2.3.4 Channel Error Statistics at Other Carrier Frequencies

The effect of variation in centre frequency on the error distributions is shown in Fig. 2.23, 2.24 with data rate set at 19,200bps. The centre frequencies chosen were at 105, 110, 120, 125KHz, and the average BER was fixed at 10^{-3}. The results obtained at the various frequencies are very similar.

Extensive measurements were then performed to record the channel error statistics when the transmission system's centre frequency was fixed at 60KHz, for various data rates. Typical results obtained are shown in Fig. 2.25-2.30. The error distributions do not show any significant difference when compared with results obtained with centre frequency at 120KHz, at comparable BER performance. This is because the

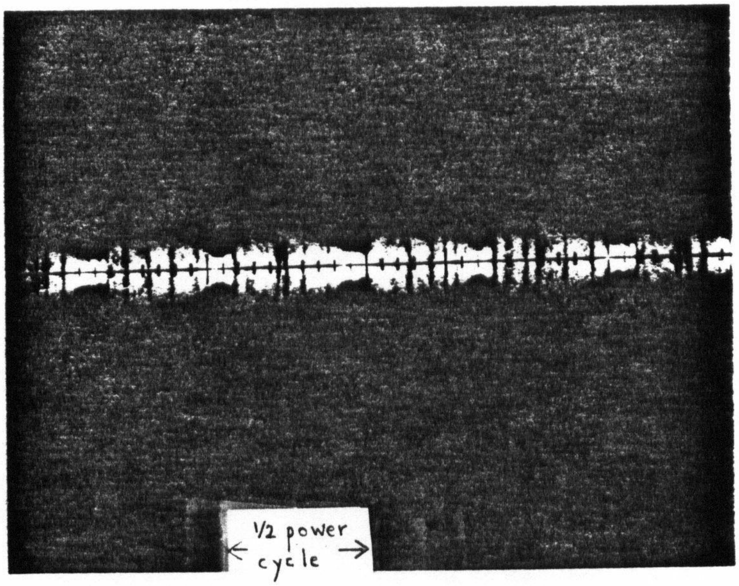


Fig. 2.22 Background power line noise. (Note: the high level impulse spikes are not shown in the picture)

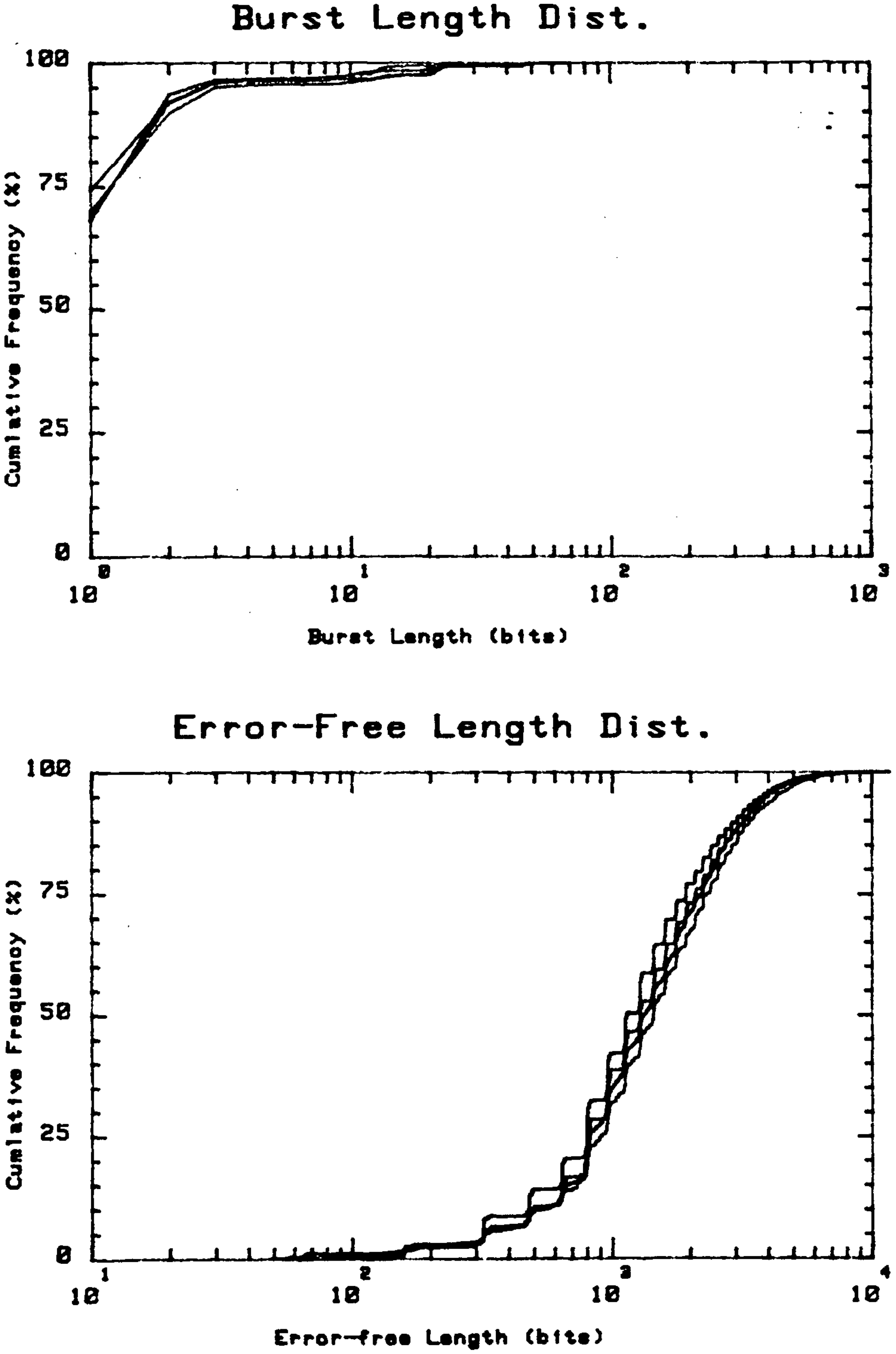
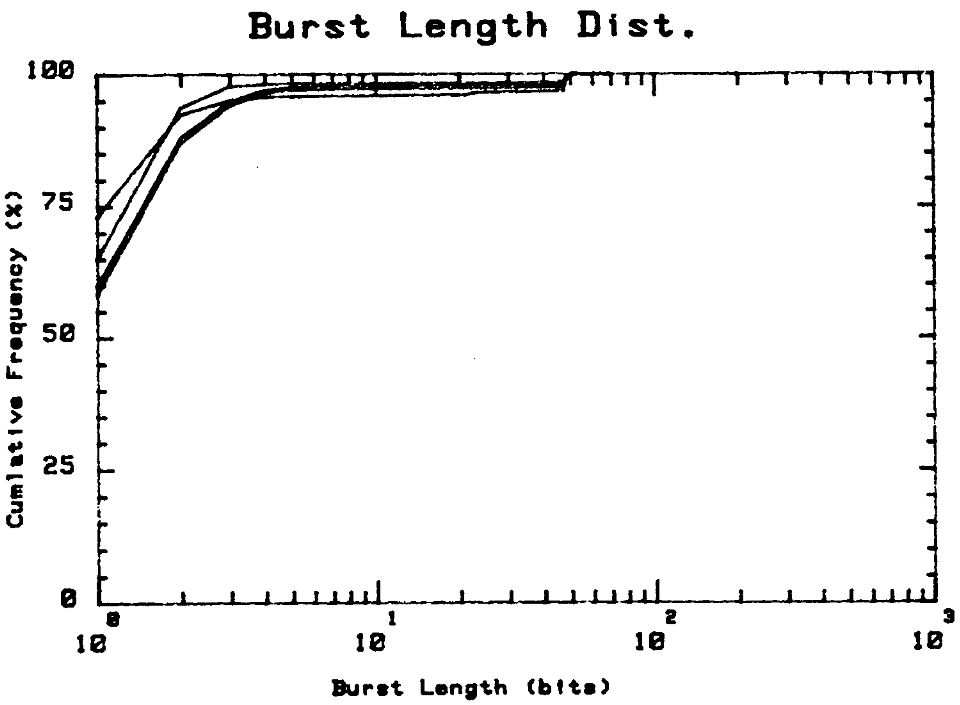


Fig. 2.23 Effect of variation of carrier frequency on error statistics. FSK: 19,200bps data rate, 105, 110, 120, 125 KHz carrier frequencies. Across-phase transmission. BER = 10^{-3} .



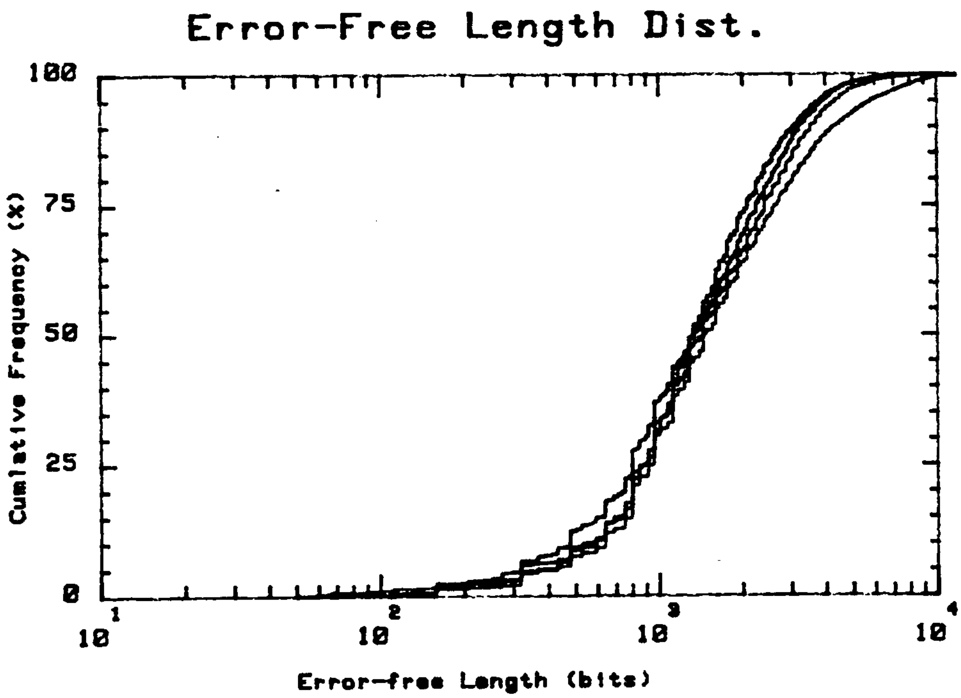
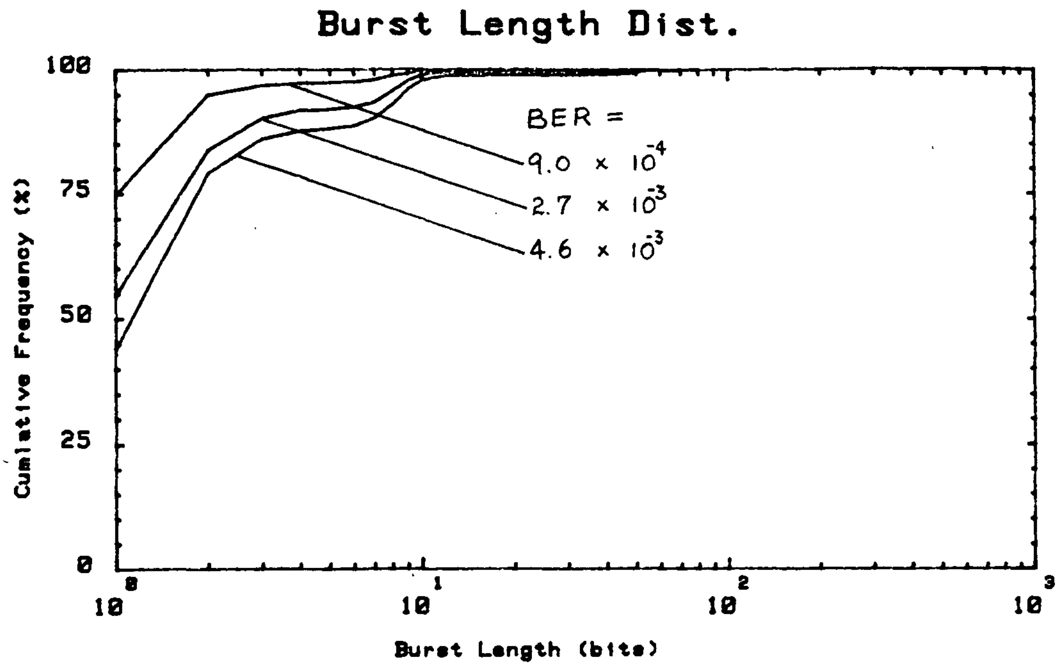


Fig. 2.24 Effect of variation of carrier frequency on error statistics. FSK: 19,200bps data rate, 105, 110, 120, 125 KHz carrier frequencies. In-phase transmission. BER = 10^{-3} .



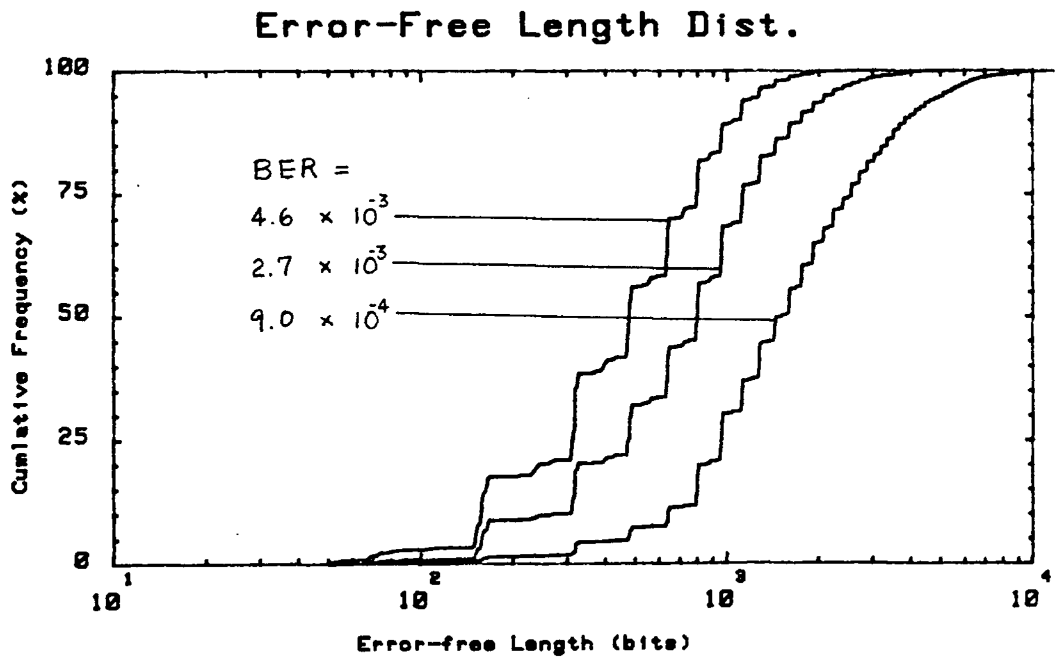
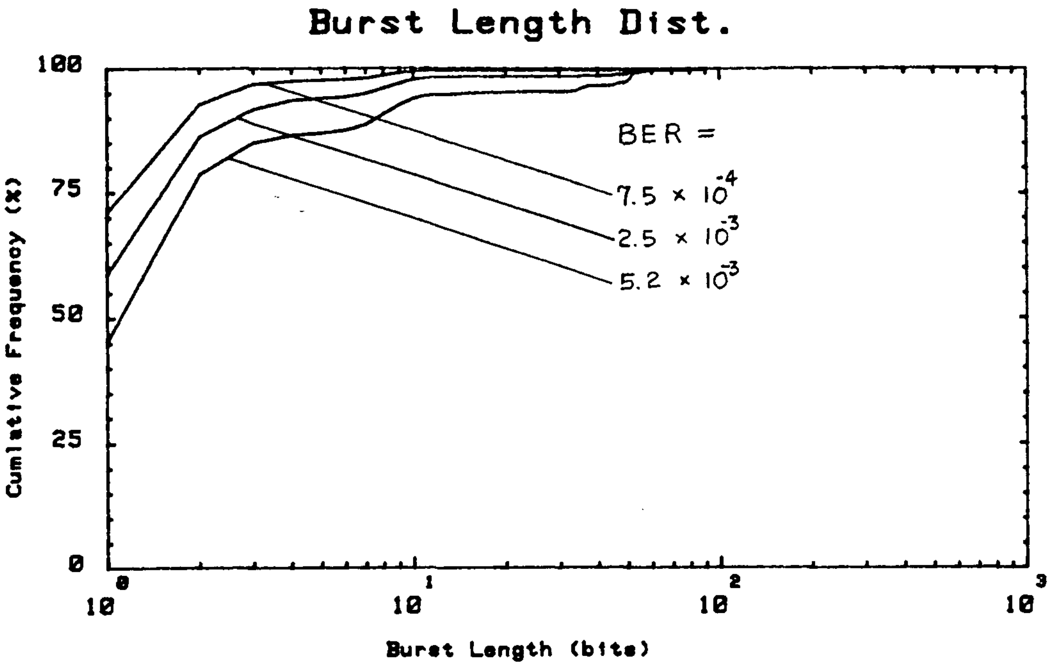


Fig. 2.25 Representative channel error statistics. FSK: 19,200bps data rate, 60KHz carrier frequency. In-phase transmission.



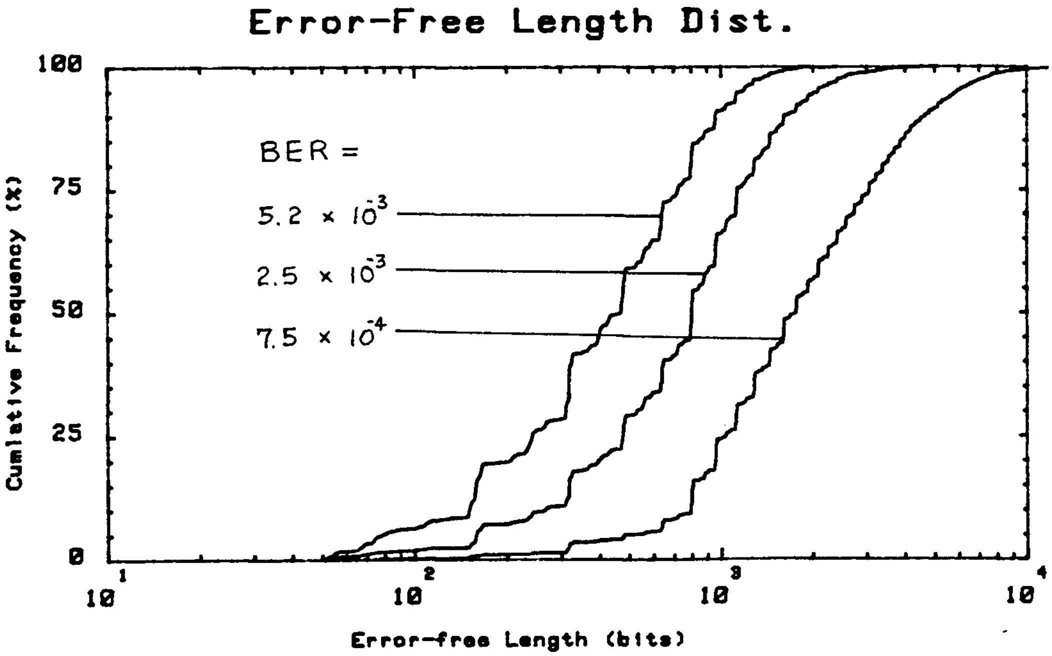
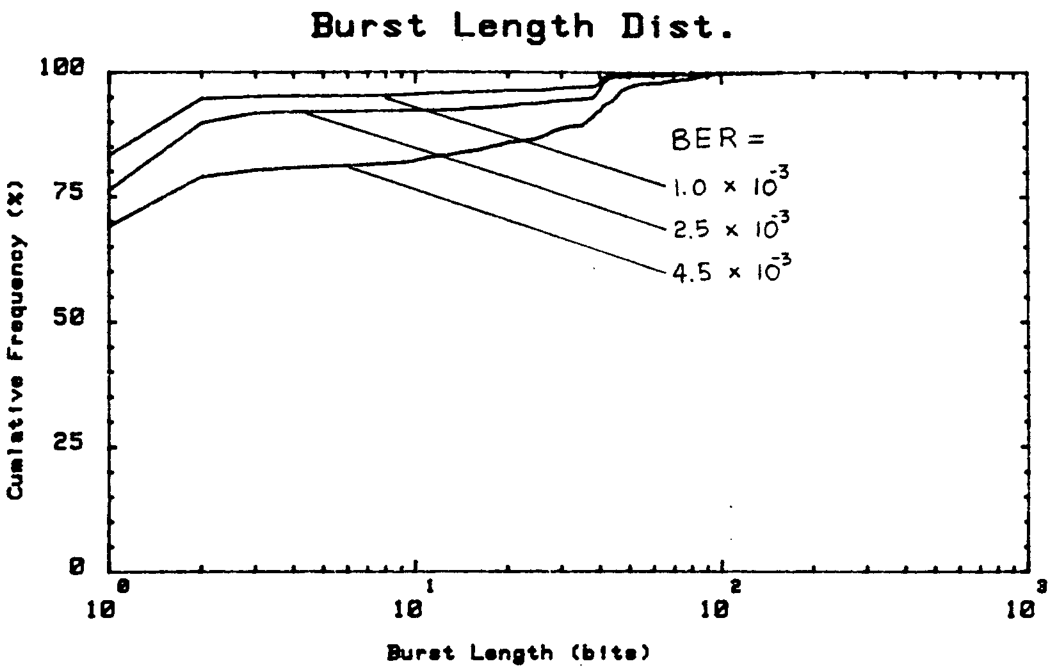


Fig. 2.26 Representative channel error statistics. FSK: 19,200bps data rate, 60KHz carrier frequency. Across-phase transmission.



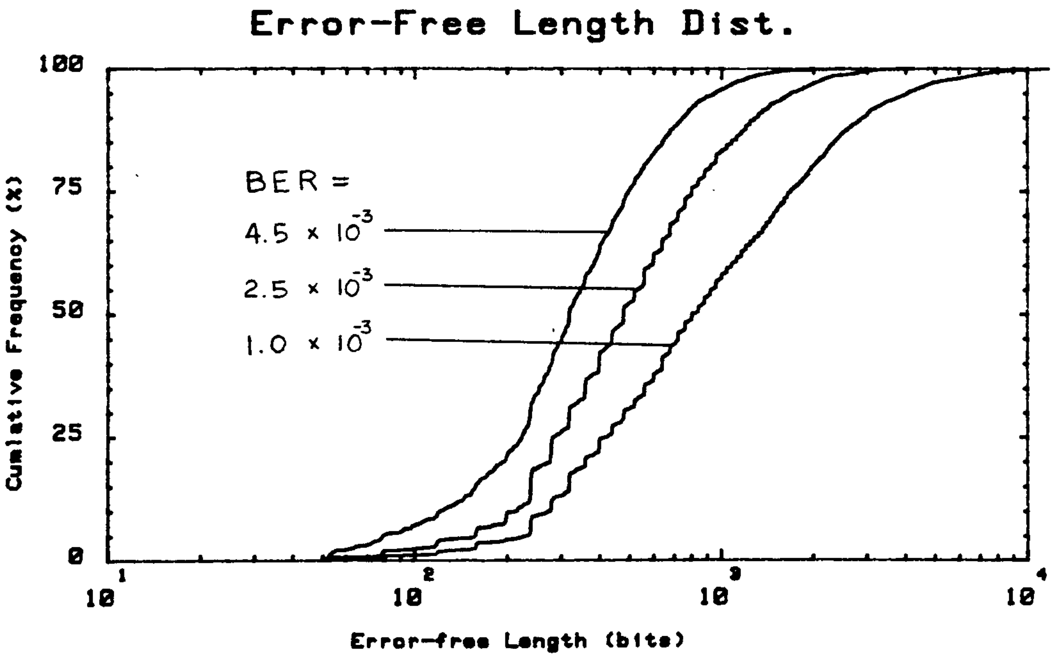
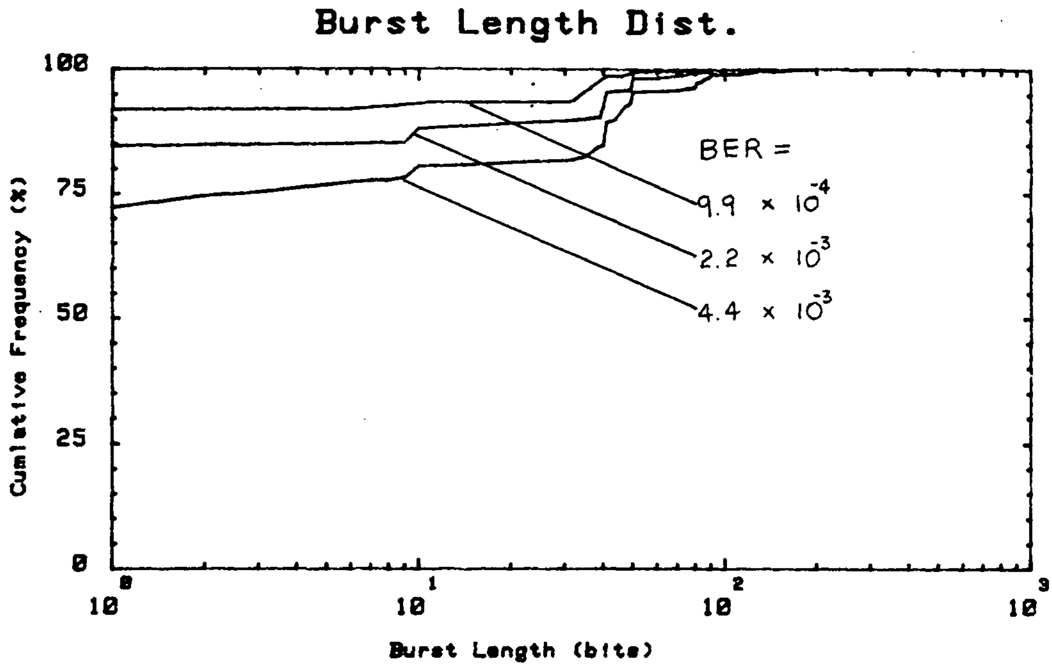


Fig. 2.27 Representative channel error statistics. FSK: 4,800bps data rate, 60KHz carrier frequency. In-phase transmission.



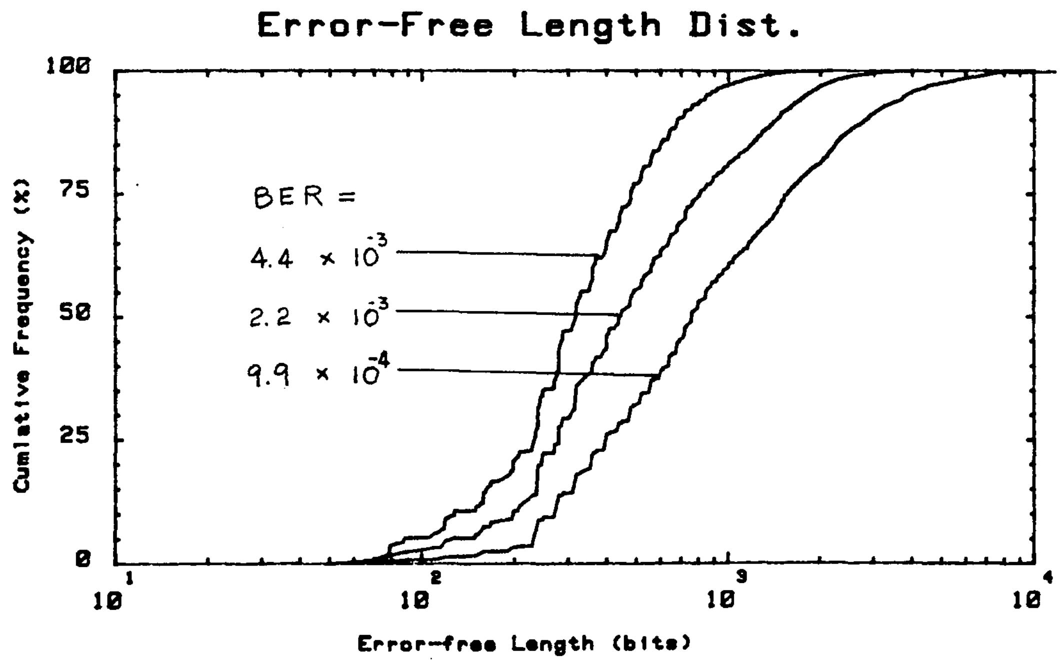
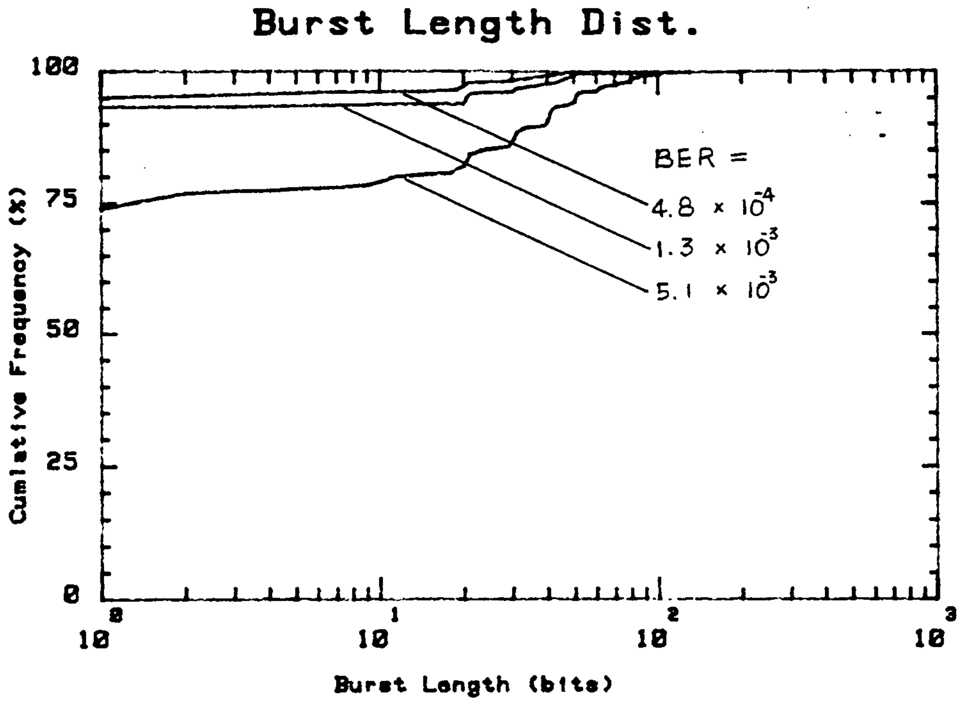


Fig. 2.28 Representative channel error statistics. FSK: 4,800bps data rate, 60KHz carrier frequency. Across-phase transmission.



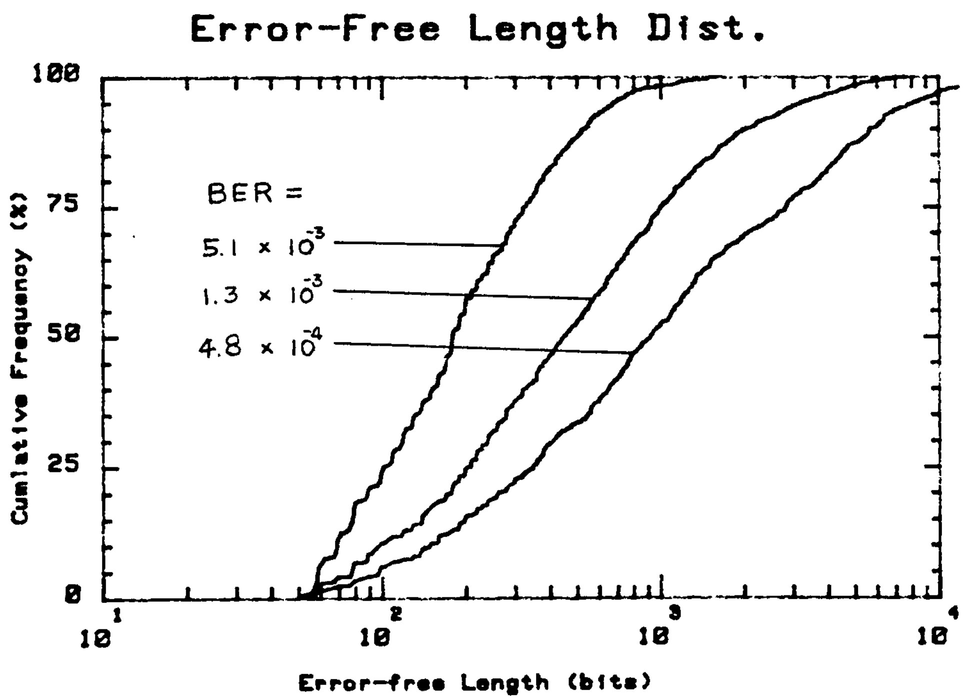
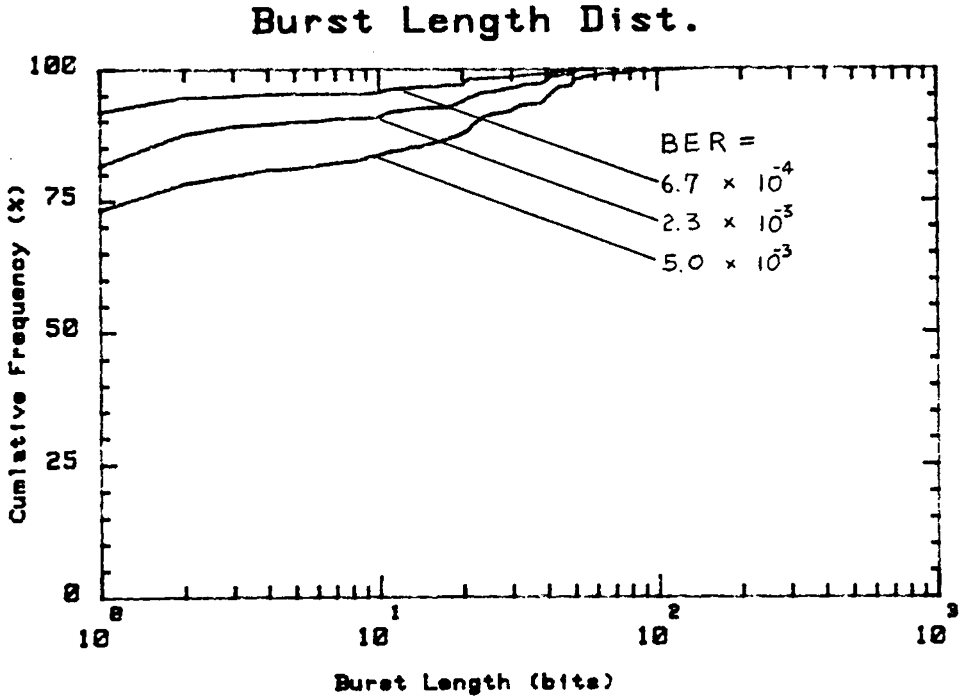


Fig. 2.29 Representative channel error statistics. FSK: 1,200bps data rate, 60KHz carrier frequency. In-phase transmission.



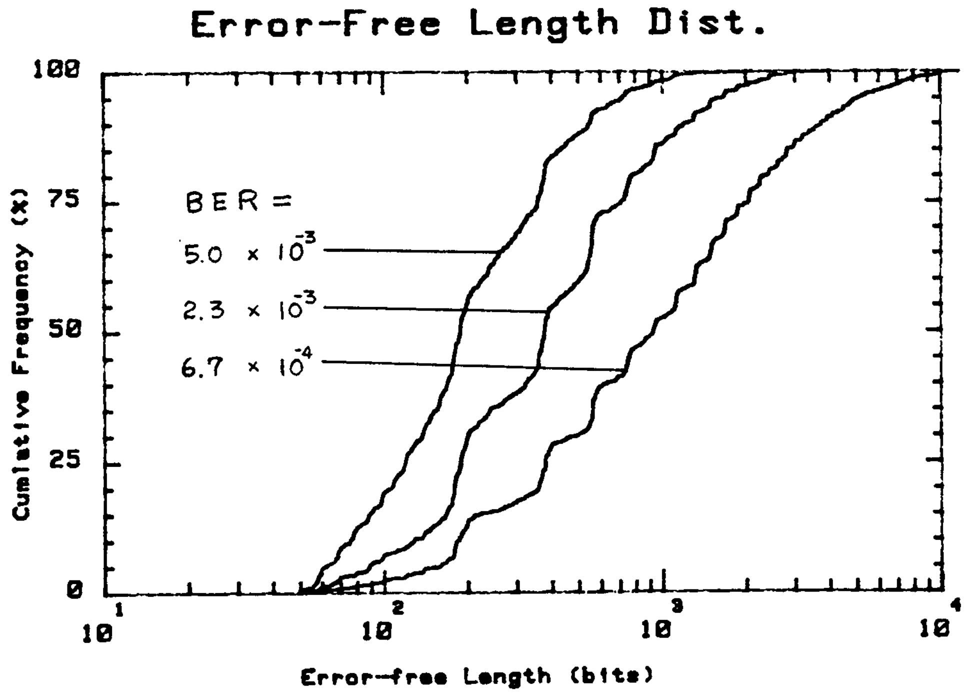


Fig. 2.30 Representative channel error statistics. FSK: 1,200bps data rate, 60ZKHz carrier frequency. Across-phase transmission.

same types of error-causing disturbances were affecting the signal transmission and reception. However, the two cases required different transmitter power levels to achieve the same BER performance. This is simply because signals operating at different frequency bands will encounter different levels of attenuation and noise. At 19,200bps data rate, typical transmitter output voltage levels used varied from 1Vrms to 4.5Vrms while at 1,200bps data rate, typical voltage level used was less than 300mVrms.

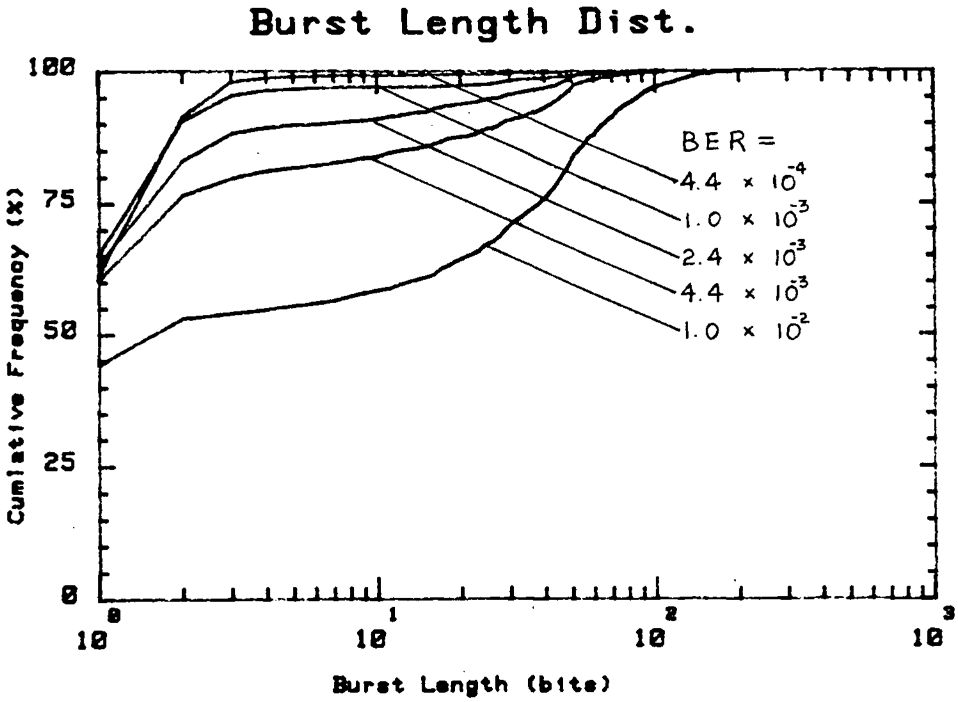
2.4 Measurement Results: Residential Apartment Complex

A residential apartment complex having approximately 50 individual units was chosen for measurement of error statistics. In such a residential building in North America, split-single-phase power is normally supplied to circuit panels inside the building by two 110-volt supply lines and one neutral line from a centre-tapped single-phase distribution transformer. Therefore, placement of the transmitter and receiver on the same side of the neutral line will herinafter be referred to as "in phase" signal transmission, while placement of the transmitter and receiver on different sides of the neutral line will hereinafter be referred to as "off phase" transmission. Measurements were made on various days and time periods to obtain error statistics at a data rate of 19,200bps and carrier frequency of 120KHz.

Error statistics for one representative measurement during in phase signal transmission appear in Fig. 2.31. During the test, periodic impulse spikes were observed to cause most of the errors, while aperiodic impulse bursts caused some additional longer error bursts. Similar results were observed for off phase signal transmission.

Impulse burst noise alone was often the dominant disturbance affecting reception. Results representative of the error behaviour exhibited during periodic impulse burst disturbance are shown in Fig. 2.32, and results representative of the error behaviour during aperiodic impulse burst disturbance are shown in Fig. 2.33. In general, impulse bursts created slightly longer burst errors than did impulse spikes.

During the entire course of the experiments, no noticeable fading effect was observed; periodic impulse spikes, periodic impulse bursts and aperiodic impulse bursts were the predominant causes of errors.



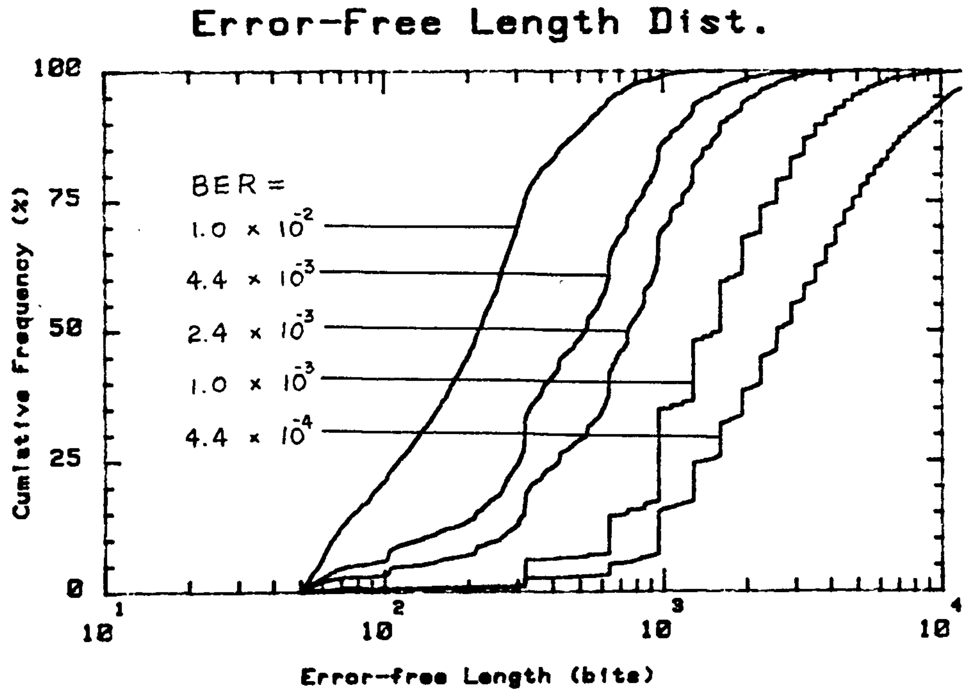
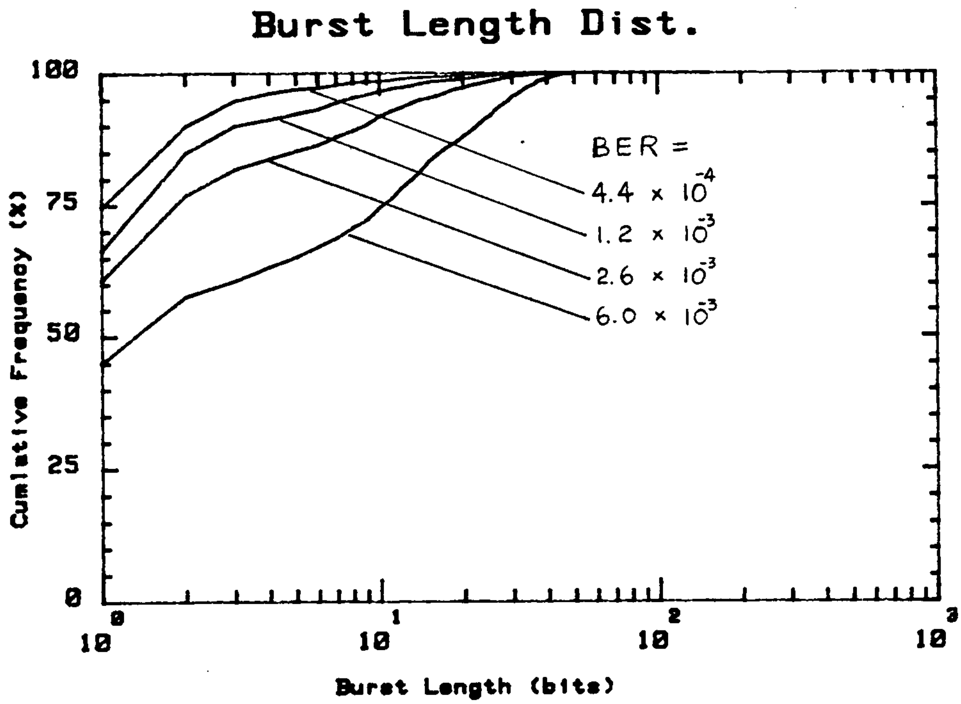


Fig. 2.31 Channel error statistics under periodic impulse spikes plus aperiodic impulse bursts impairment. FSK: 19,200bps data rate, 120KHz carrier frequency. In-phase transmission.



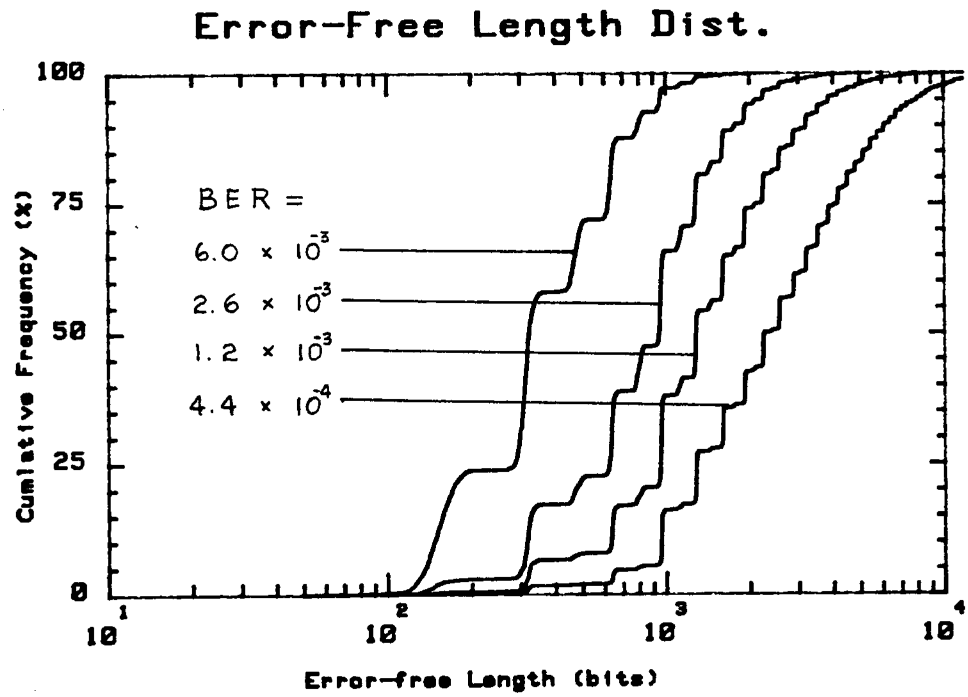
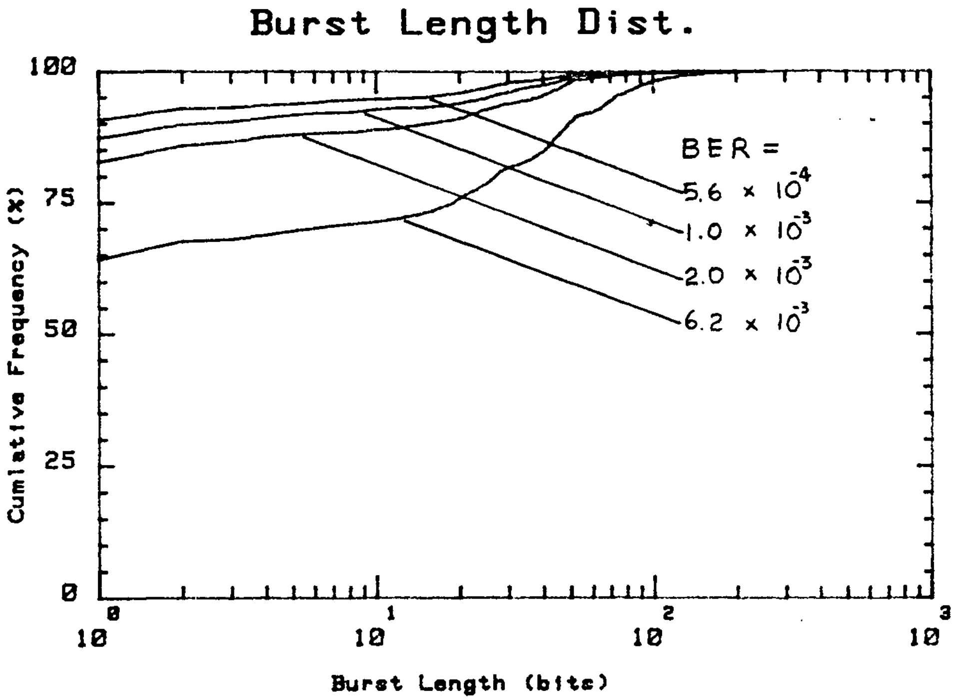


Fig. 2.32 Channel error statistics under periodic impulse bursts impairment. FSK: 19,200bps data rate, 120KHz carrier frequency. Off-phase transmission.



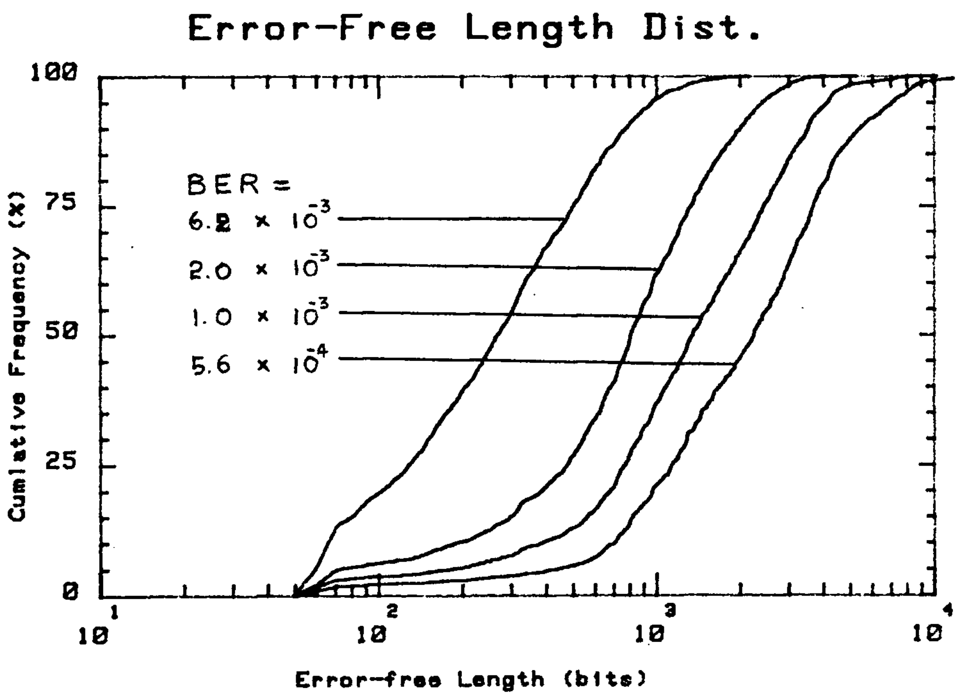


Fig. 2.33 Channel error statistics under aperiodic impulse bursts impairment. FSK: 19,200bps data rate, 120KHz carrier frequency. In-phase transmission.

3. CHANNEL ERROR STATISTICS FOR A PSK SYSTEM

Measurement of error statistics for a PSK system operating on intrabuilding power line channels were made in the same industrial building described in chapter 2. Results were obtained for various data rates (1,200-38,400bps) at a carrier frequency of 115KHz during various days and time periods. The measuring system and procedure remained the same except that the transmitter was a PSK modulator and the receiver had the structure shown in Fig. 3.1.

3.1 The PSK Receiver

General probability of error expressions for coherent PSK and differential coherent DPSK Systems in the presence of both impulsive and Gaussian noise have been derived and analysed [13]. The PSK receiver model used in the above study is shown in Fig. 3.1. The band pass filter's 3-dB bandwidth was about 40KHz centered around the carrier frequency. Coherent demodulation was achieved by using a separate timing signal derived from the power line voltage to synchronize both the transmitter and receiver. Tests of the modem in the presence of additive white gaussian noise confirms proper functioning of the modem hardware.

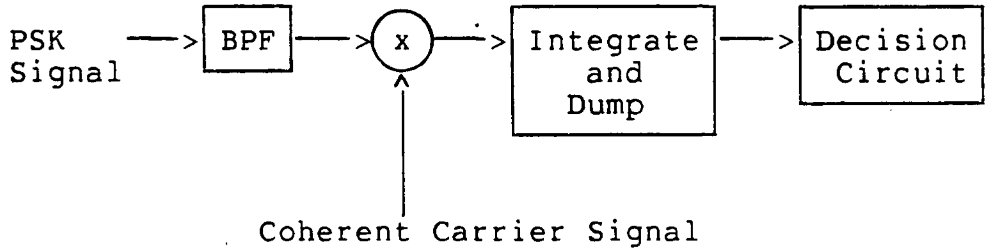


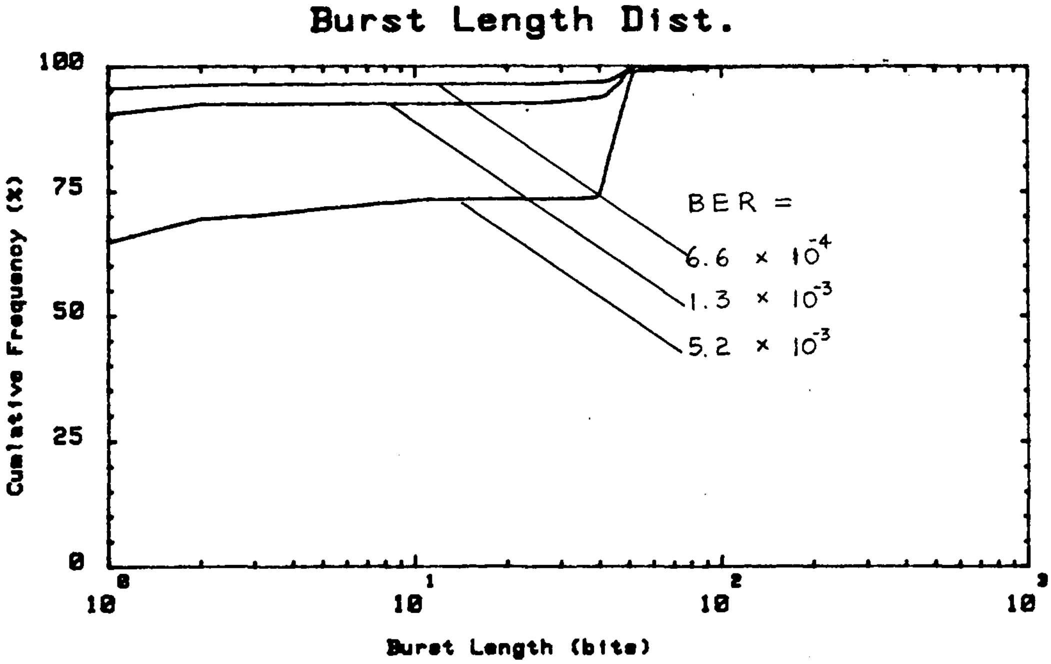
Fig. 3.1 PSK receiver [13].

3.2 Measurement Results: 38,400bps Data Rate

The error distribution for one representative in phase signal transmission is shown in Fig. 3.2. The curves show that most of the errors (over 90%) are single bit errors for values of BER equals to 10^{-3} or smaller. Results for representative across phase signal transmission is shown in Fig. 3.3. Again, the majority of the errors are single bit errors. Typical transmission voltage levels used in this case varied between 0.5Vrms to 3.5Vrms.

3.3 Measurement Results: 19,200bps Data Rate

Error statistics for representative in phase and across phase signal transmission are shown in Fig. 3.4, 3.5. No significant difference is shown between results obtained at 19,200bps and 38,400bps data rate. Periodic impulse noise spikes were again the predominant causes of errors. When



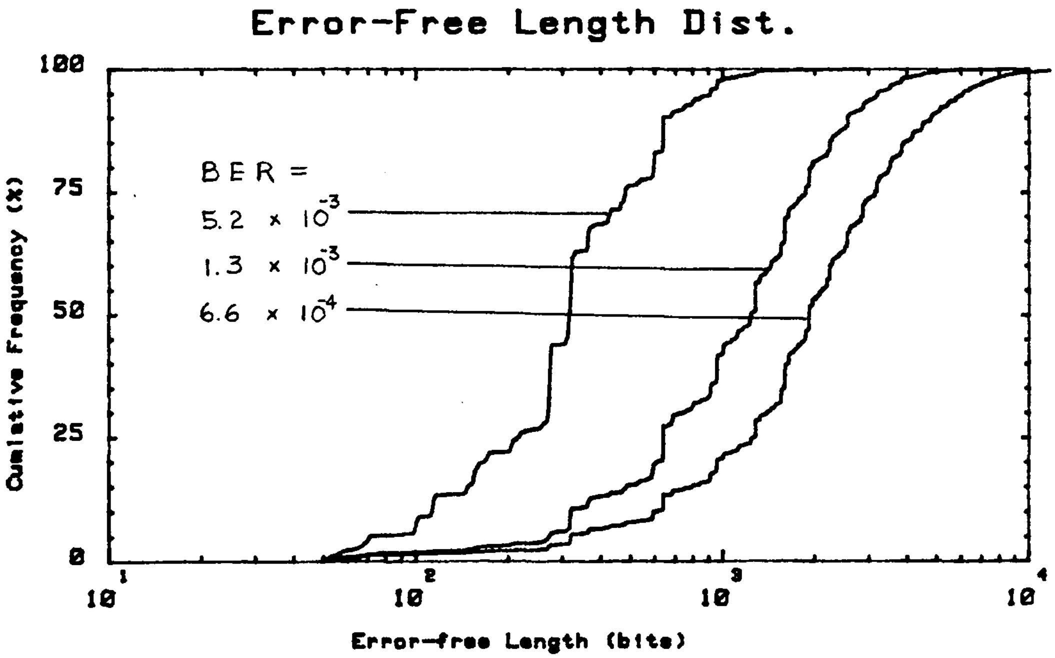
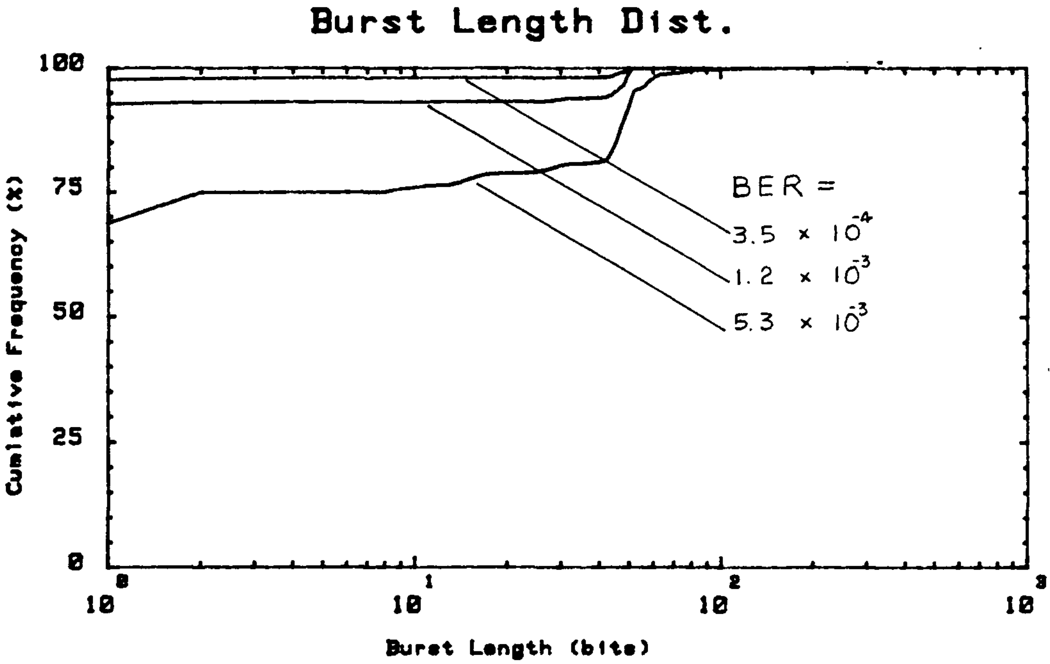


Fig. 3.2 Representative channel error statistics. PSK: 38,400bps data rate, 115KHz carrier frequency. In-phase transmission.



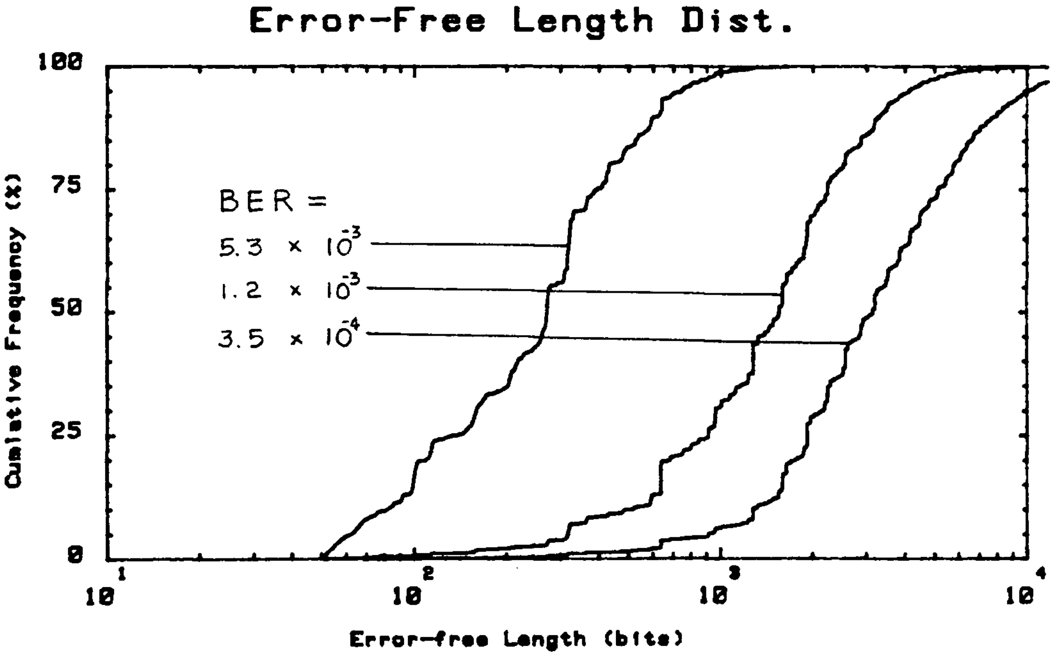


Fig. 3.3 Representative channel error statistics. PSK: 38,400bps data rate, 115KHz carrier frequency. Across-phase transmission.

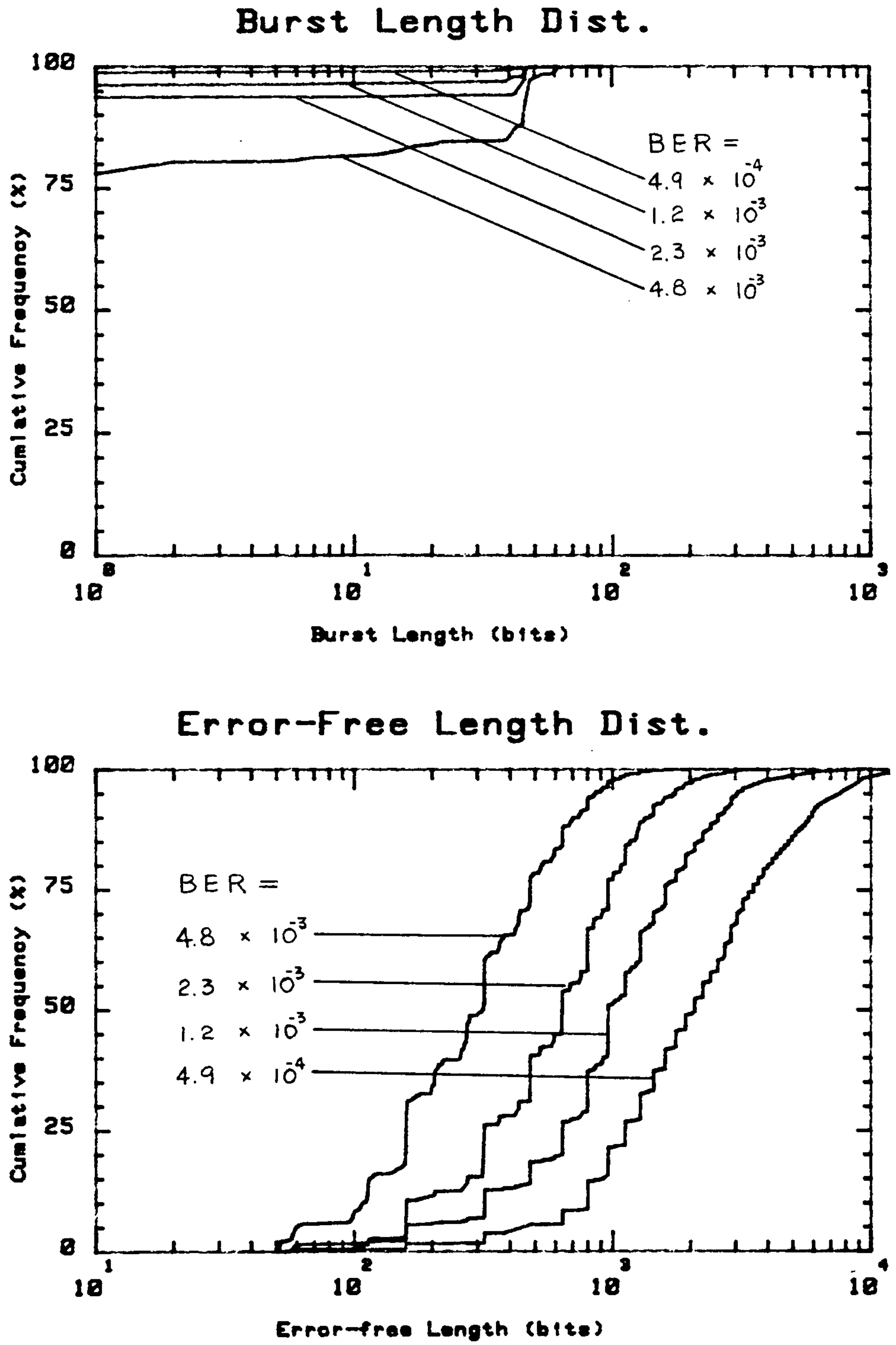
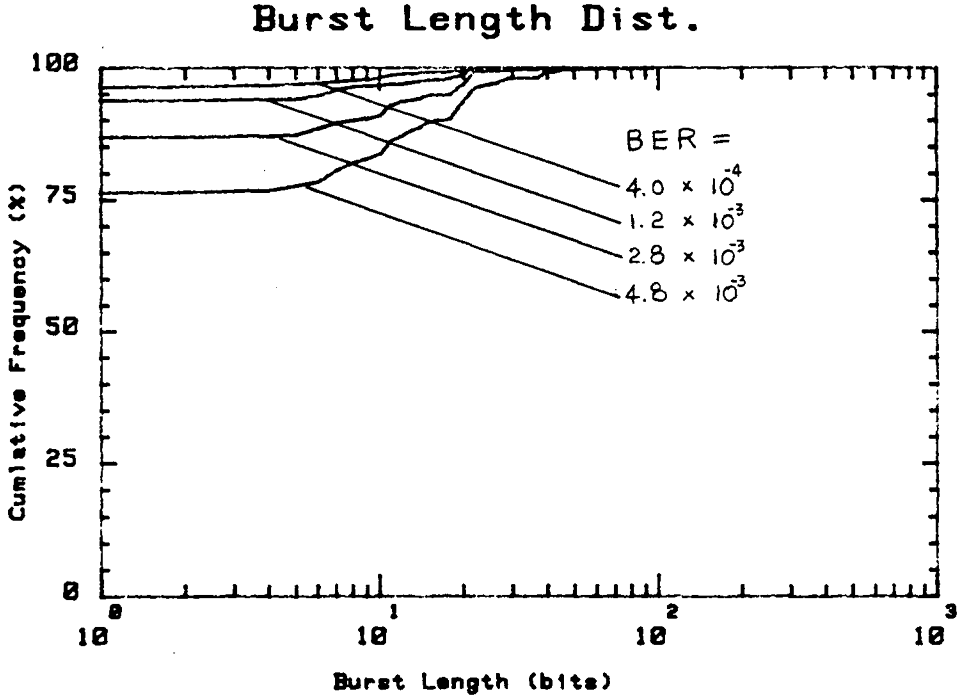


Fig. 3.4 Representative channel error statistics. PSK: 19,200bps data rate, 115KHz carrier frequency. In-phase transmission.



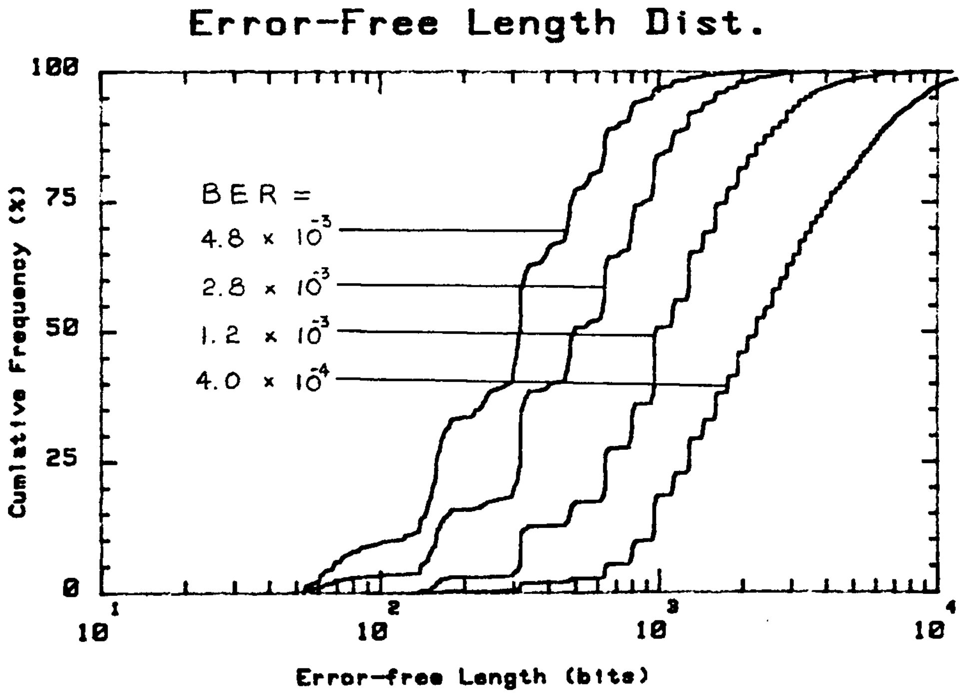


Fig. 3.5 Representative channel error statistics. PSK: 19,200bps data rate, 115KHz carrier frequency. Across-phase transmission.

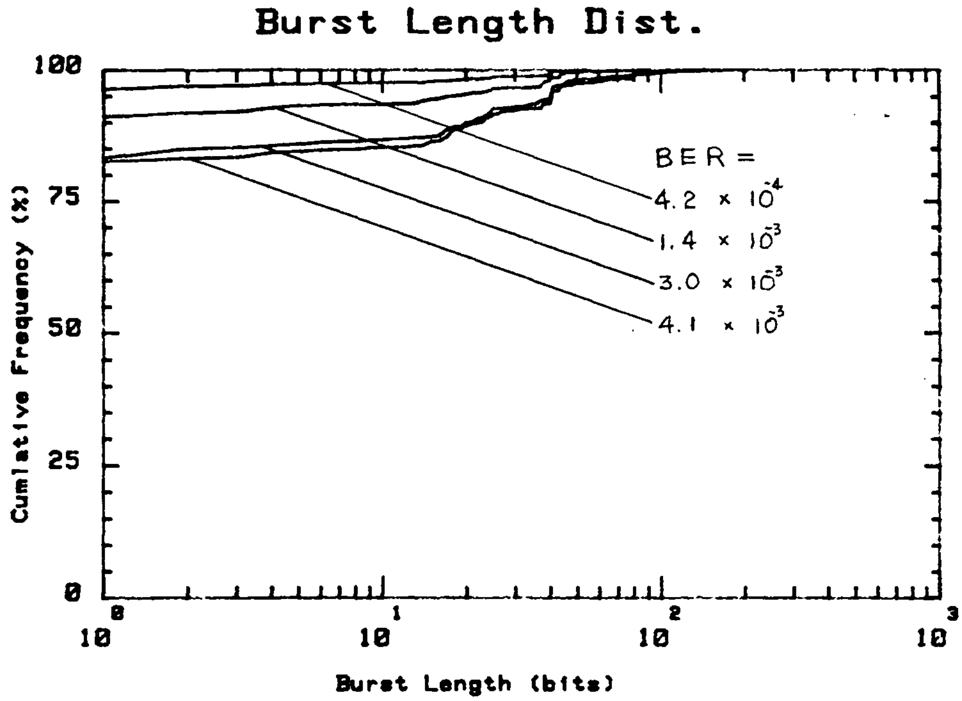
compared with the FSK system bearing the same average BER performance, the results consistently indicate that PSK gives a higher percentage of single bit errors and a lower percentage of double and triple bit errors. Thus, the probability of an impulse noise spike causing multiple errors appears smaller in PSK than in FSK, probably because of the 3dB advantage inherent in the PSK signalling scheme. However, more measurements are required to confirm this hypothesis. Otherwise, PSK and FSK give similar performance as both are vulnerable to the harmful effects of impulse noise.

Impulse noise is commonly found in a number of channels, including operational multichannel satellite systems and terrestrial microwave systems. The general performance of systems in the presence of impulsive noise alone, or combinations of impulsive and Gaussian noise has been analysed by others [13-20], and general probability of error expressions for various modulation schemes due to these disturbances are available. In particular, the error probability performance of PSK and DPSK systems was compared in [13] and was found to exhibit little difference. It was concluded [13] that impulse noise, at the instant when it enters the receiver, causes an error with high probability independent of the signalling scheme.

Furthermore, for impulse noise limited channels, the error probability verses the received signal-to-noise ratio curve does not follow the exponential shape exhibited under Gaussian noise disturbance. Indeed, the curve begins to bottom out in the high signal-to-noise ratio region. The resulting slow drop of BER is very serious when the data bit duration is comparable to the impulse spike duration, and dictates that appropriate error control be used in high speed power line communications. (Details regarding error control appear in chapter 5).

3.4 Measurement Results: 4,800bps and 1,200bps Data Rate

Representative results obtained at these data rates are shown in Fig. 3.6 and 3.7. The results are consistent with those obtained in chapter 2 using the FSK modem.



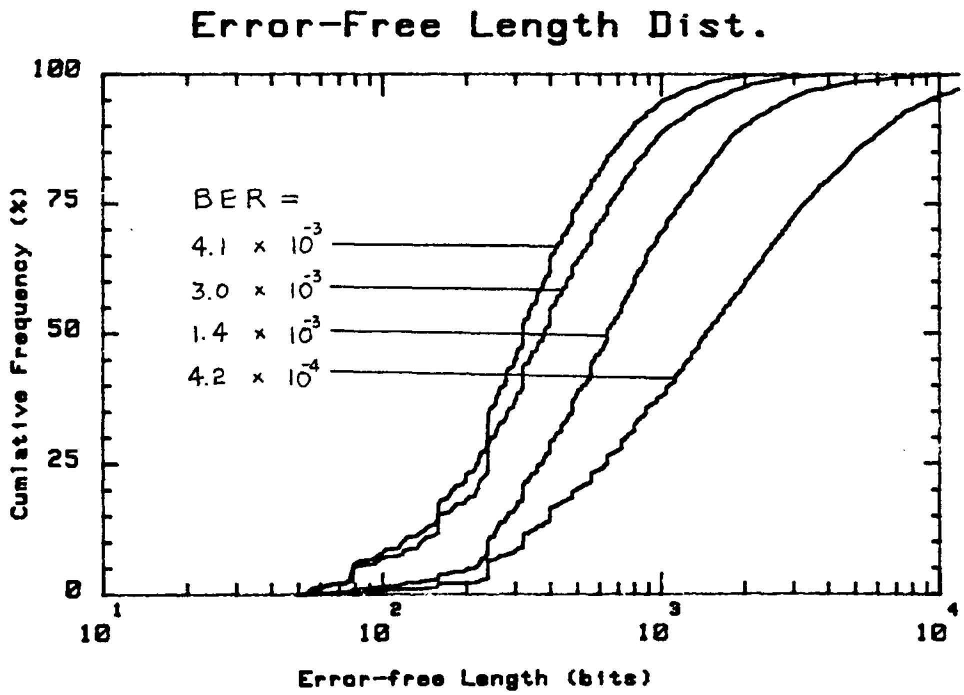
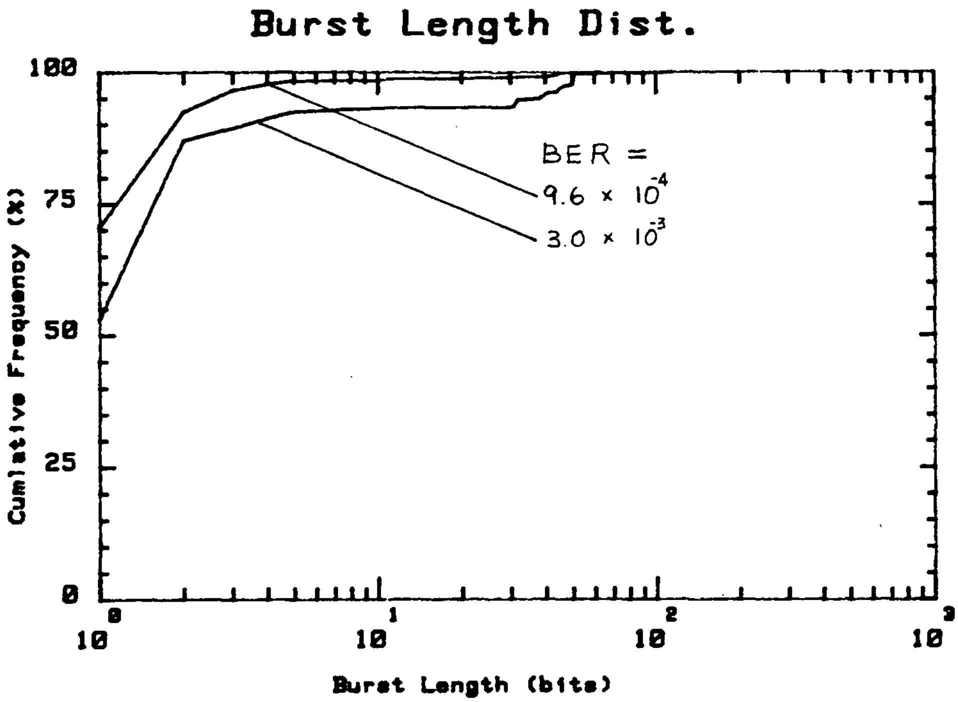


Fig. 3.6 Representative channel error statistics. PSK: 4,800bps data rate, 115KHz carrier frequency. Across-phase transmission.



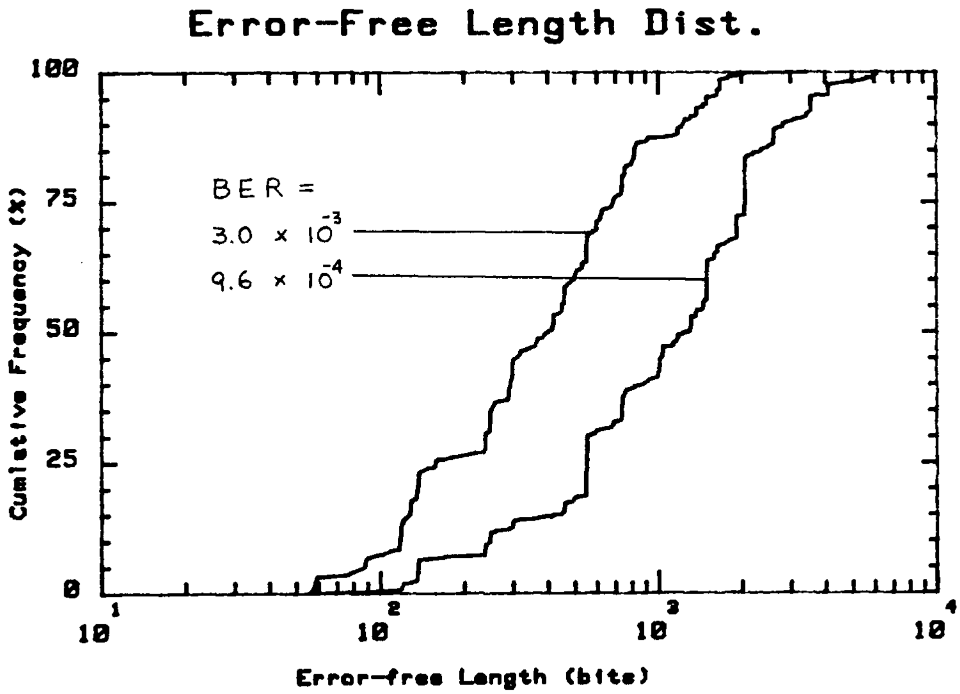


Fig. 3.7 Representative channel error statistics. PSK: 1,200bps data rate, 115KHz carrier frequency. Across-phase transmission.

4. CHANNEL ERROR STATISTICS FOR SPREAD SPECTRUM SYSTEMS

Spread spectrum signalling provides a means of information transmission in which the information signal uses a bandwidth larger than the minimum necessary to transmit the information [21]. The spectrum spreading process is achieved by using a pseudorandom code which is independent of the data. At the receiver, the same code sequence is used to despread the signal back to its original bandwidth.

There are various ways that the code can be used for spectrum spreading. Two common techniques are direct-sequence (DS) and frequency-hopping (FH). In a DS system, the information signal is multiplied with the pseudonoise code to generate a transmitted signal whose bandwidth is then determined by the code rate. The factor by which the bandwidth is spread or the "processing gain" is equal to Rc/Rd where Rc and Rd denote the code rate and data rate, respectively. In a FH system, the code is used to shift the transmission frequency in a pseudorandom manner. If there are N frequency slots available, and one frequency slot is used every T seconds, then the total bandwidth of the system is approximately equal to N/T [21].

Advantages of spread spectrum (SSMA) signalling include resistance to narrow band impartments, multiple user random access capability, selective addressing capability and immunity to casual eavesdropping. Primary disadvantages include code acquisition delay, as well as increased hardware complexity and implementation costs.

Measurements of channel error statistics were made using a DS/SSMA-FSK system and a DS/SSMA-PSK system. The tests were conducted during various days and time periods in the same industrial building described in chapter 2. Results were obtained at various data rates, code rates and carrier frequencies. The measuring system and procedure remained the same as before except that DS/SSMA-FSK and DS/SSMA-PSK modems were used.

4.1 Direct-Sequence SSMA Frequency-Shift-Keyed (DS/SSMA-FSK) System

4.1.1 The Transmitter and Receiver

The transmitter and receiver block diagrams for the DS/SSMA-FSK system are shown in Fig. 4.1.

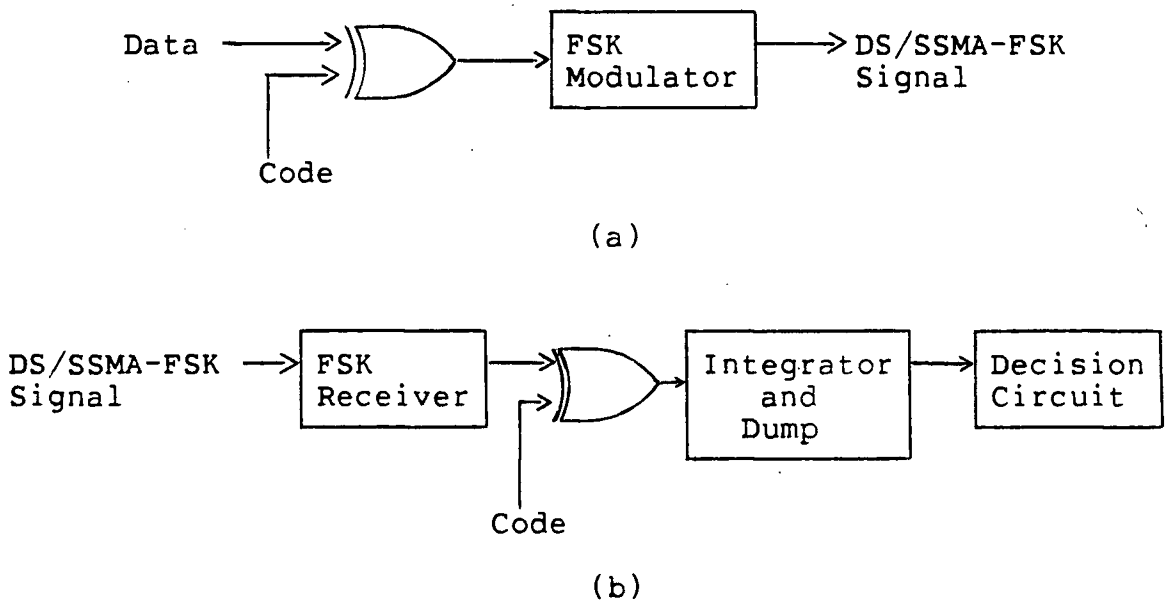


Fig. 4.1 (a) DS/SSMA-FSK transmitter,
(b) DS/SSMA-FSK receiver

The transmitter consists of a pseudorandom code sequence generator and the FSK modulator used in chapter 2. The data message is first multiplied by the code sequence and the resulting data modulated code sequence is then used as the input signal to the FSK modulator.

The received signal is first demodulated by the FSK demodulator to recover the data modulated code sequence which is then correlated with the locally generated code sequence. A majority decision using an integrate and dump filter is then employed to extract the data. Code synchronization is done by using standard "search and lock" process employing sliding correlator and tracking [24,28].

4.1.2 Channel Error Statistics: 4,800bps Data Rate, 19,200bps Code Rate, 120KHz Carrier Frequency

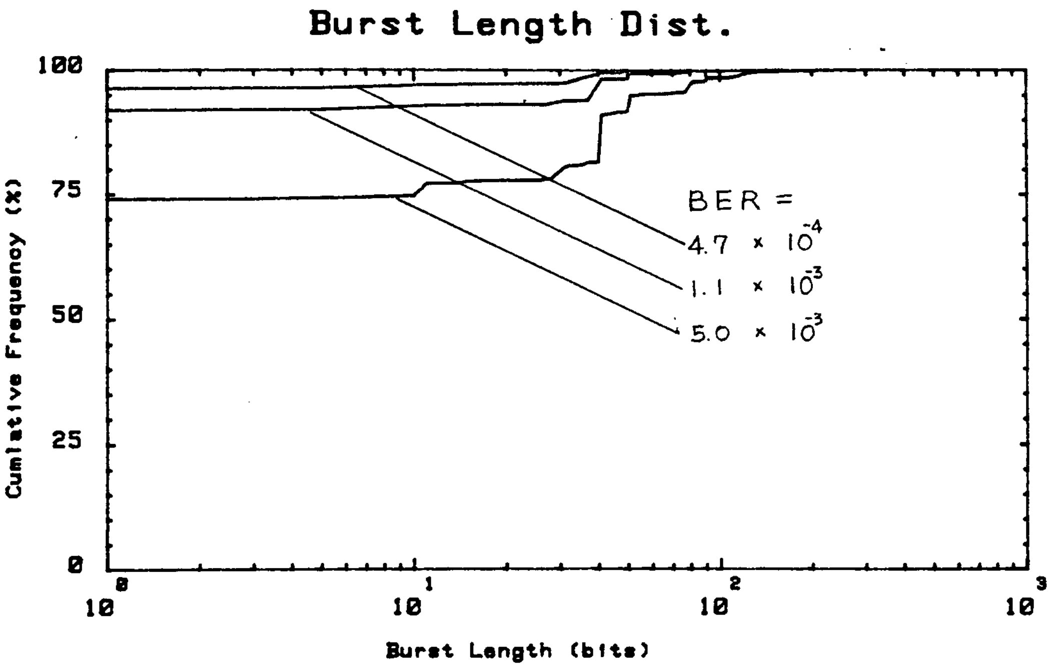
Representative error statistics for 4,800bps data rate transmission are presented in Fig. 4.2 and 4.3. The 4,800bps system represents a 3 out of 4 majority decision at the receiver.

For the same value of BER, the measured error statistics are similar to the FSK results in chapter 2. Impulsive noise spikes caused many single bit errors. Typical transmitter voltage levels used in this case varied between .4Vrms to 1.5Vrms.

4.1.3 Channel Error Statistics: 1,200bps Data Rate, 19,200bps Code Rate, 120KHz Carrier Frequency

Representative error statistics for 1,200bps data rate system are presented in Fig. 4.4, 4.5. The 1,200bps system represents a 9 out of 16 majority decision at the receiver.

Again the measured results do not indicate any significant difference when compared with FSK results in



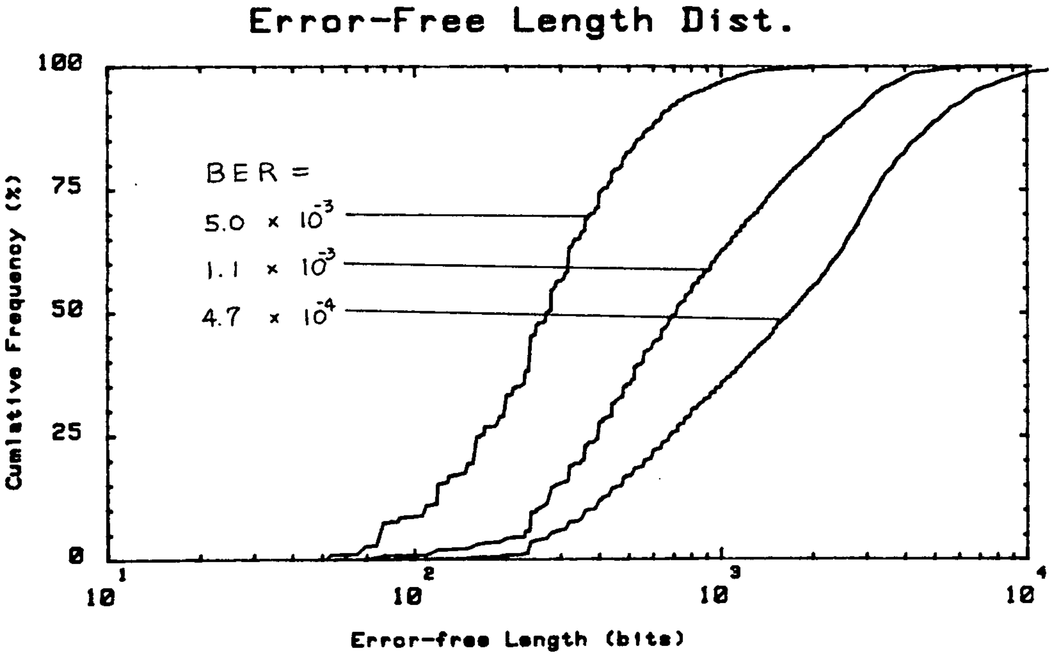
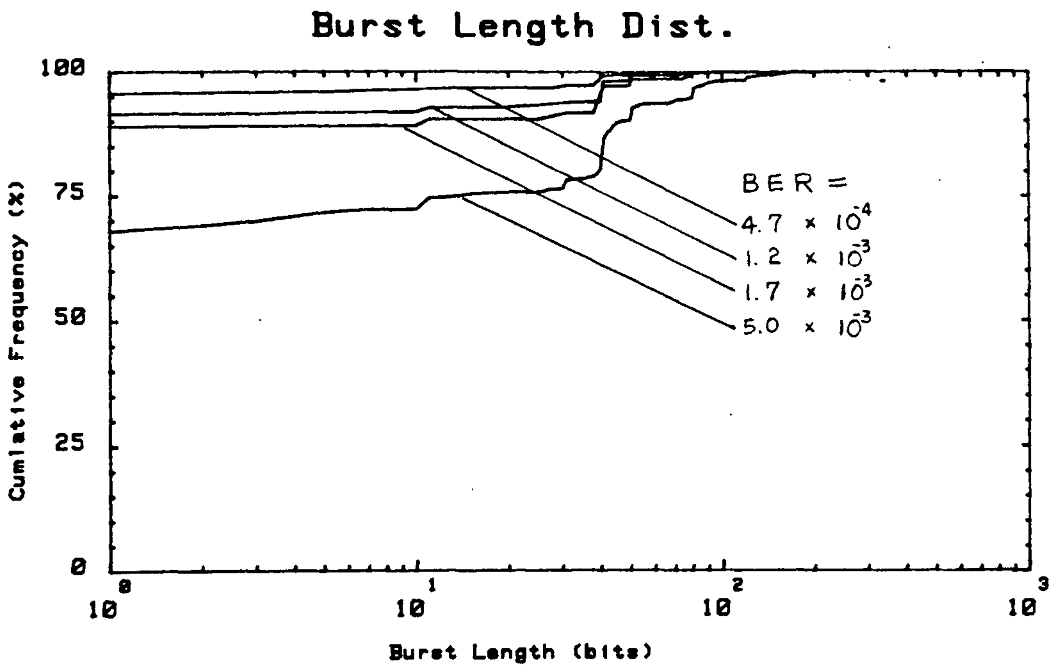


Fig. 4.2 Representative channel error statistics. DS/SSMA-FSK: 4,800bps data rate, 19,200bps code rate, 120KHz carrier frequency. In-phase transmission.



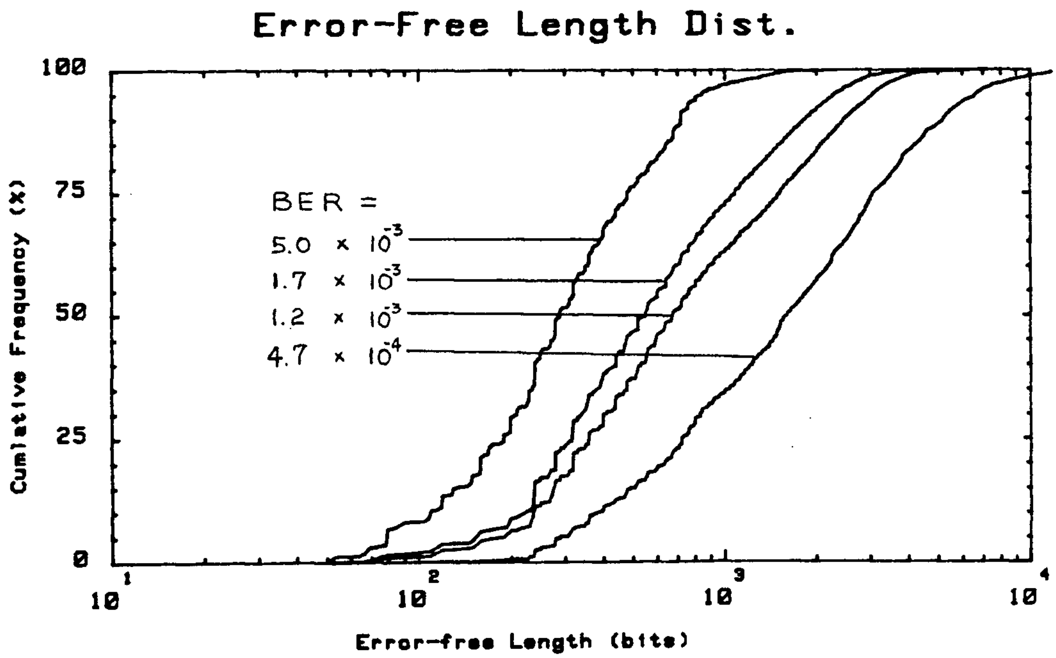
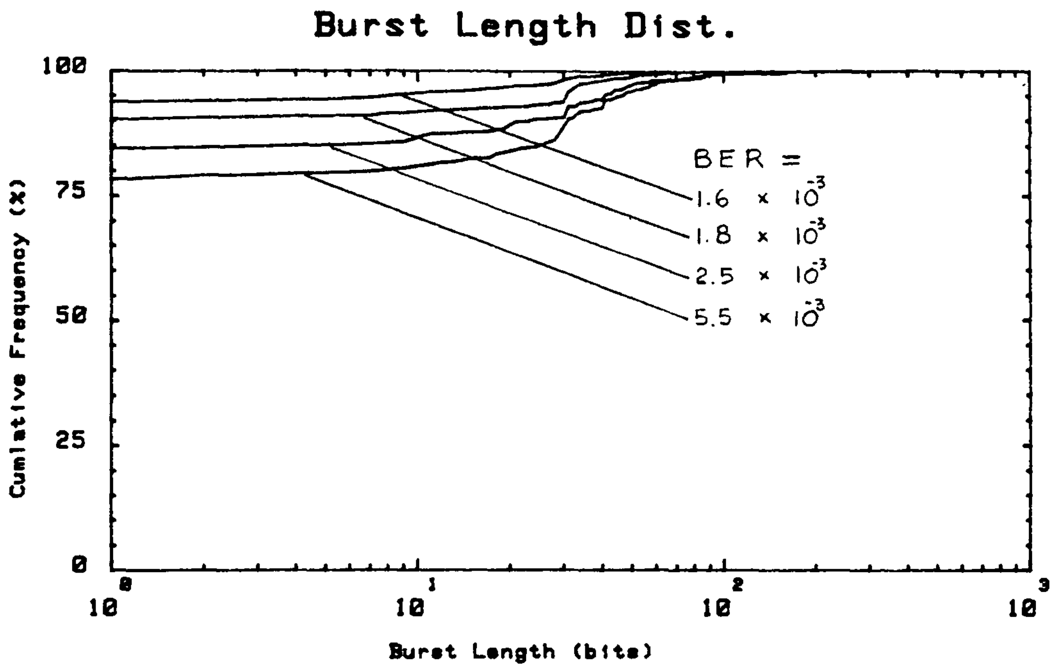


Fig. 4.3 Representative channel error statistics. DS/SSMA-FSK: 4,800bps data rate, 19,200bps code rate, 120KHz carrier frequency. Across-phase transmission.



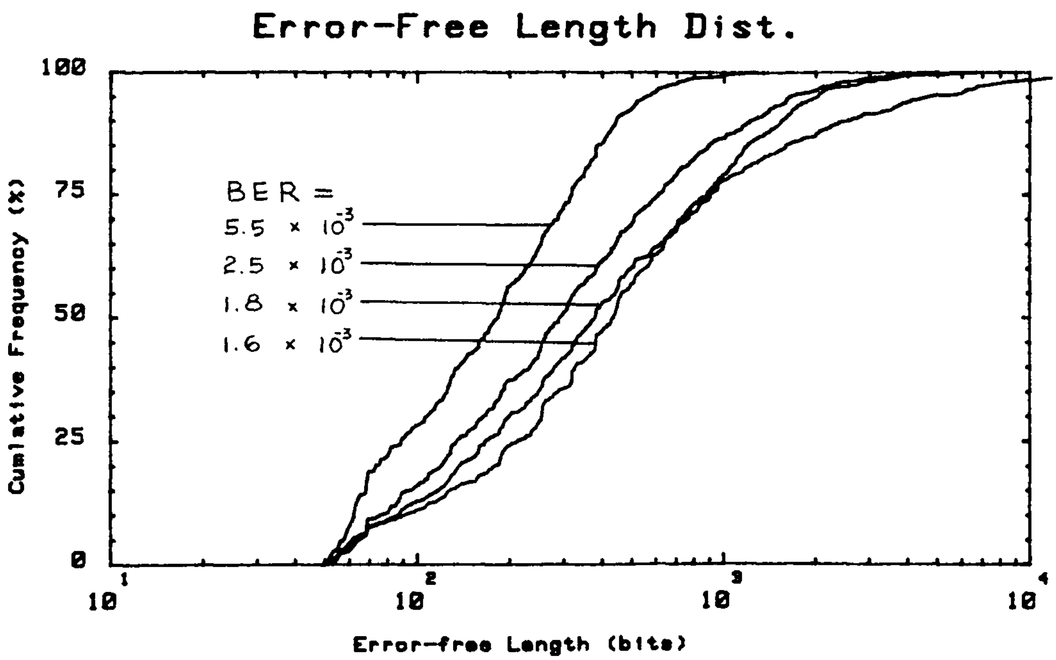
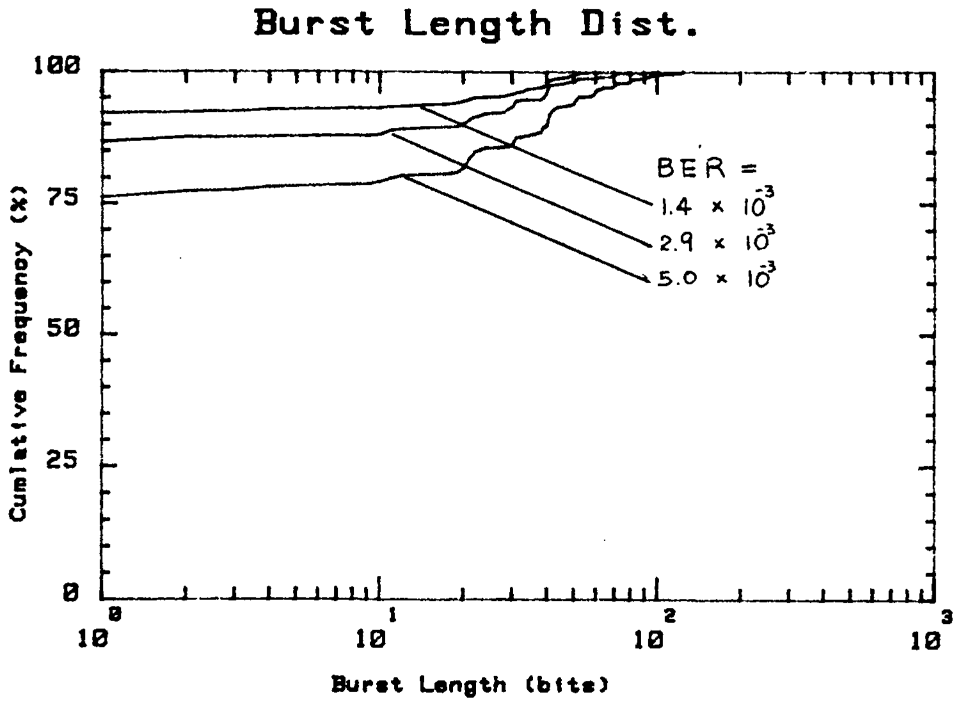


Fig. 4.4 Representative channel error statistics. DS/SSMA-FSK: 1,200bps data rate, 19,200bps code rate, 120KHz carrier frequency. In-phase transmission.



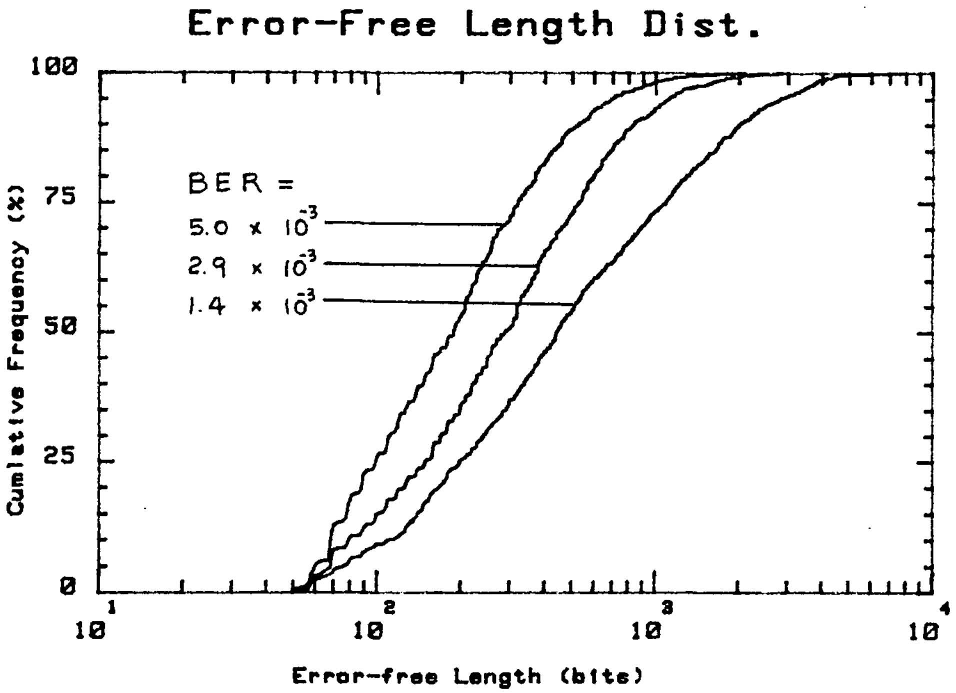


Fig. 4.5 Representative channel error statistics. DS/SSMA-FSK: 1,200bps data rate, 19,200bps code rate, 120KHz carrier frequency. Across-phase transmission.

chapter 2. Typical transmitter voltage level used was less than 300mVrms.

4.1.4 Channel Error Statistics at 60KHz Carrier Frequency

Extensive measurements were also made to record error statistics using 60KHz as the center frequency at 4,800bps and 1,200bps data rate. The results obtained again (Fig. 4.6-4.7) indicate that error pattern behaviour is insensitive to change in operating frequency.

4.2 Direct-Sequence SSMA Phase-Shift-Keyed (DS/SSMA-PSK) System

4.2.1 The Transmitter and Receiver

The transmitter and receiver block diagrams for the DS/SSMA-PSK system appear in Fig. 4.8.

The transmitter consists of a pseudorandom code sequence generator and the PSK modulator used in Chapter 3. The data message is first multiplied by the code sequence and resulting data modulated code sequence is then used as the PSK modulator input signal.

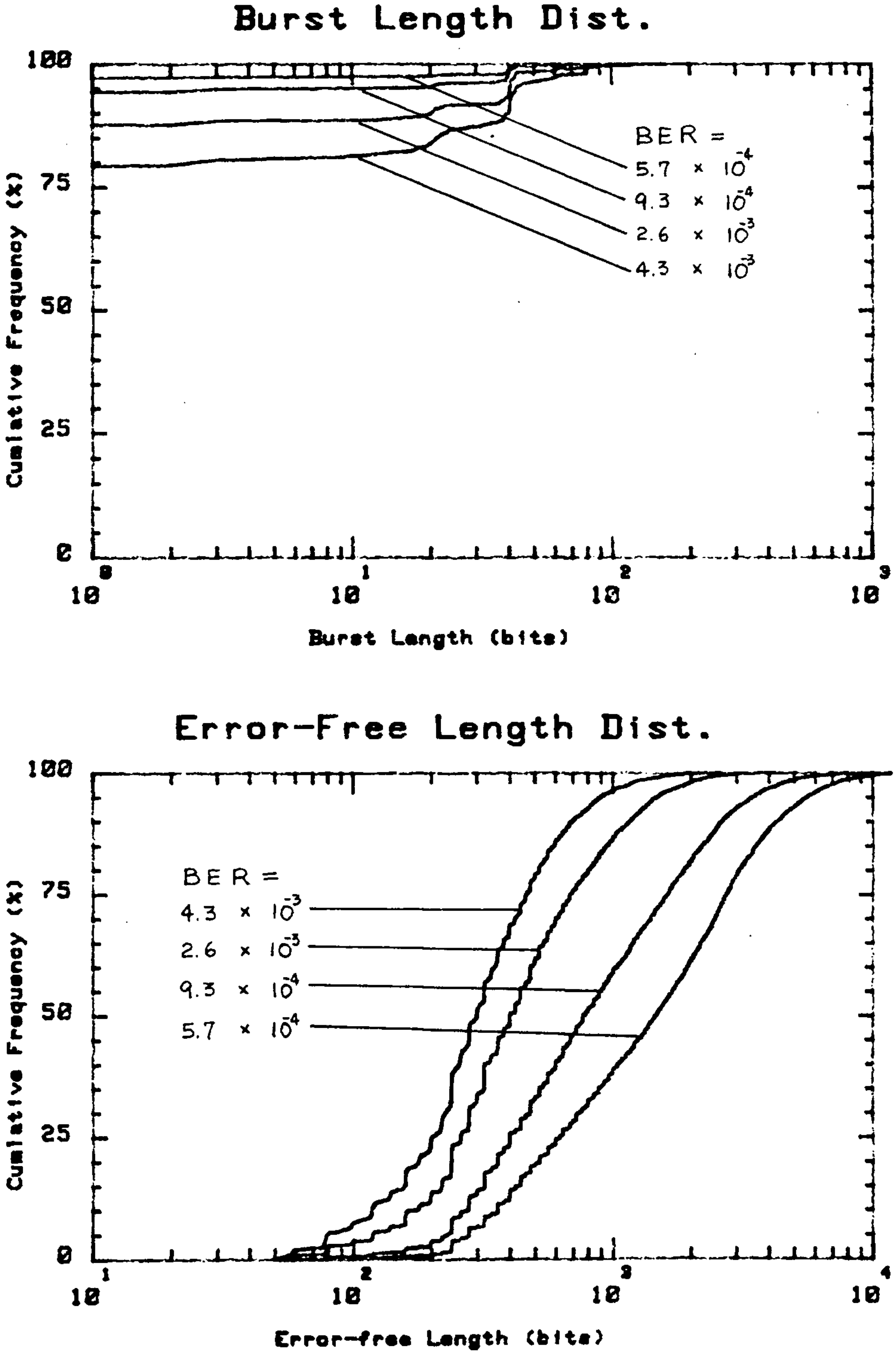
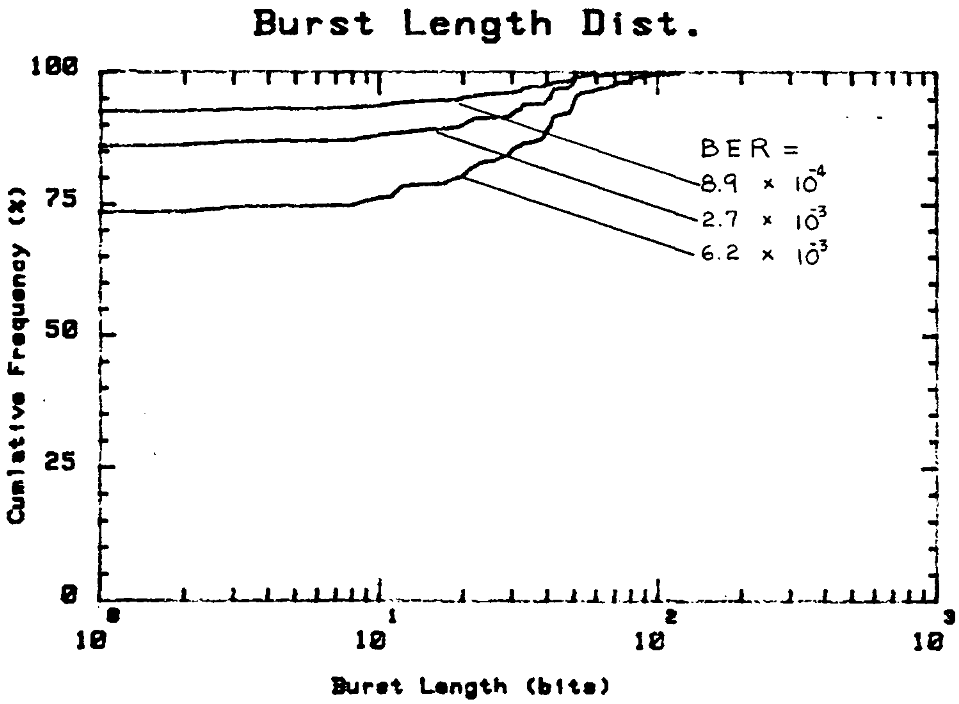


Fig. 4.6 Representative channel error statistics. DS/SSMA-FSK: 4,800bps data rate, 19,200bps code rate, 60KHz carrier frequency. Across-phase transmission.



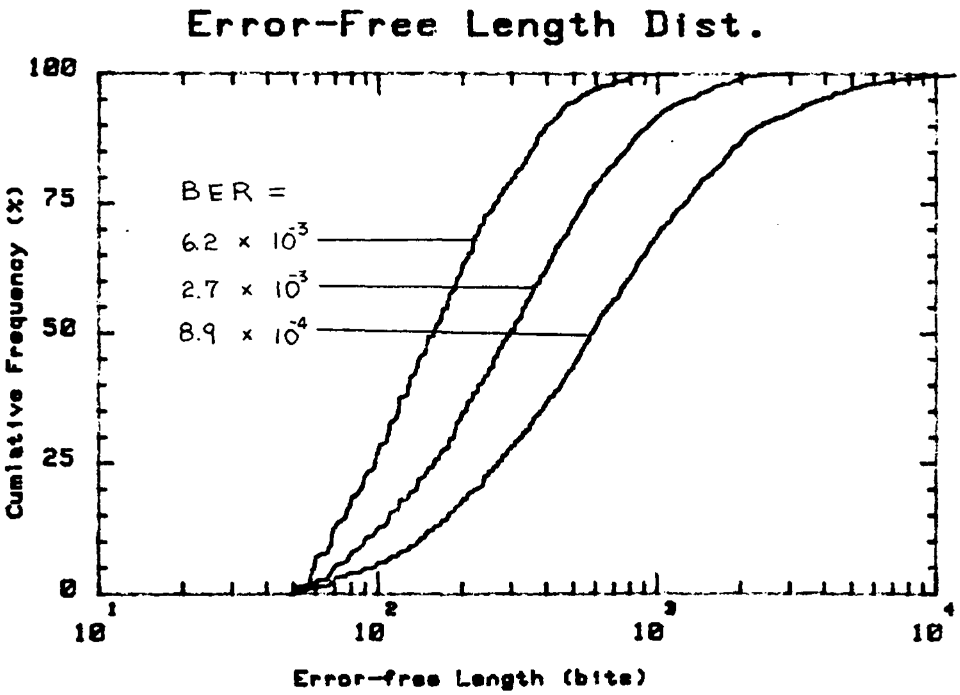
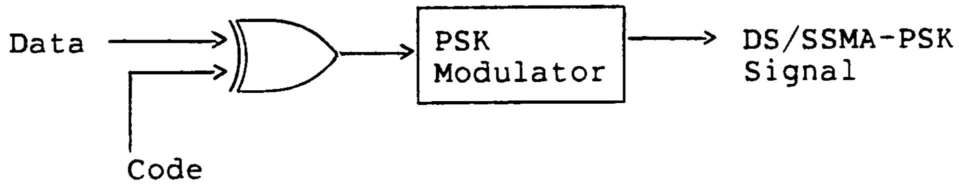
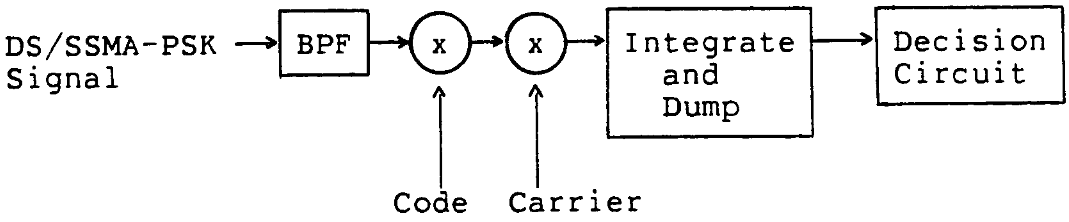


Fig. 4.7 Representative channel error statistics. DS/SSMA-FSK: 1,200bps data rate, 19,200bps code rate, 60KHz carrier frequency. Across-phase transmission.



(a)



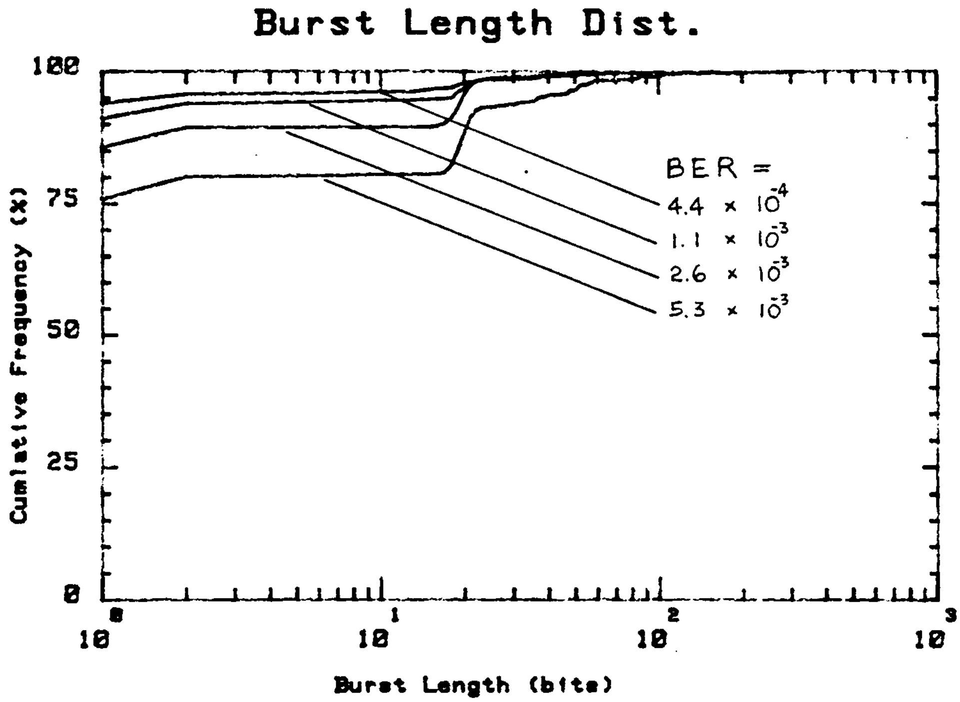
(b)

Fig. 4.8 (a) DS/SSMA-PSK transmitter,
(b) DS/SSMA-PSK receiver

The received signal is correlated with the locally generated code sequence and carrier signal, followed by an integrate and dump filter to extract the data. A separate timing signal derived from the power line voltage is used to synchronize the operation of the transmitter and receiver.

4.2.2 Channel Error Statistics: 38,400bps Code Rate, 115KHz Carrier Frequency

Representative error statistics for 19,200bps and 4,800bps data transmission are presented in Fig. 4.9, 4.10



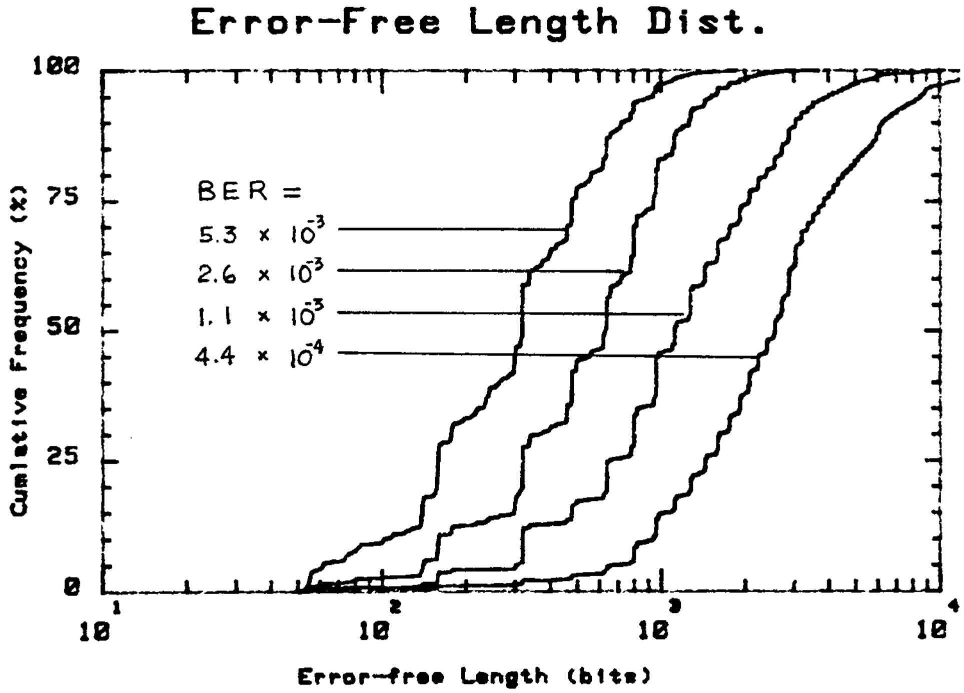
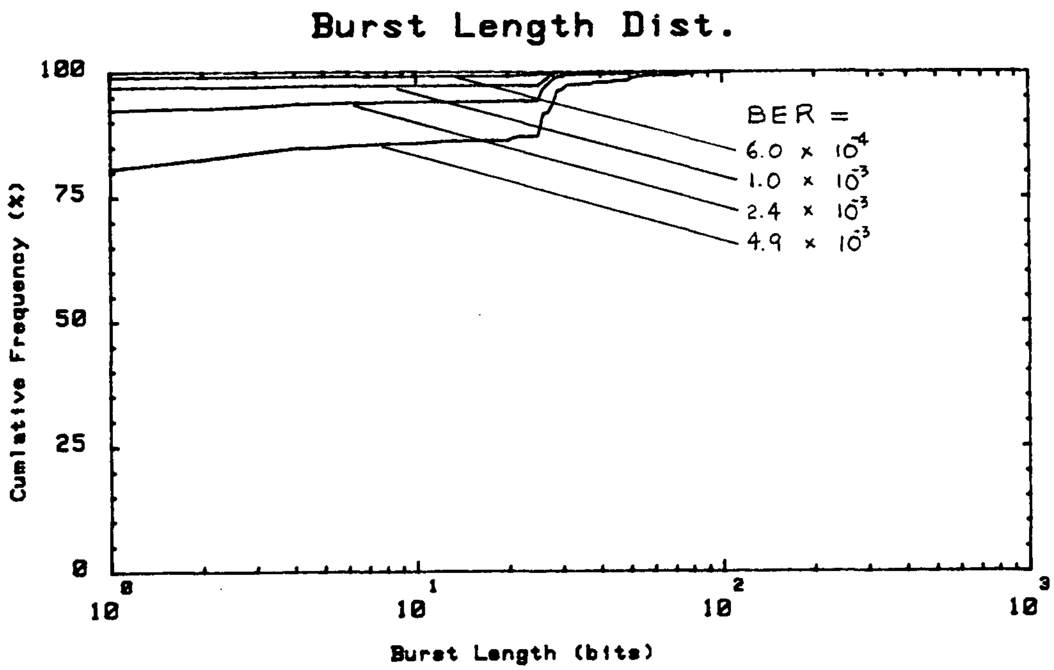


Fig. 4.9 Representative channel error statistics. DS/SSMA-PSK: 19,200bps data rate, 38,400bps code rate, 115KHz carrier frequency. Across-phase transmission.



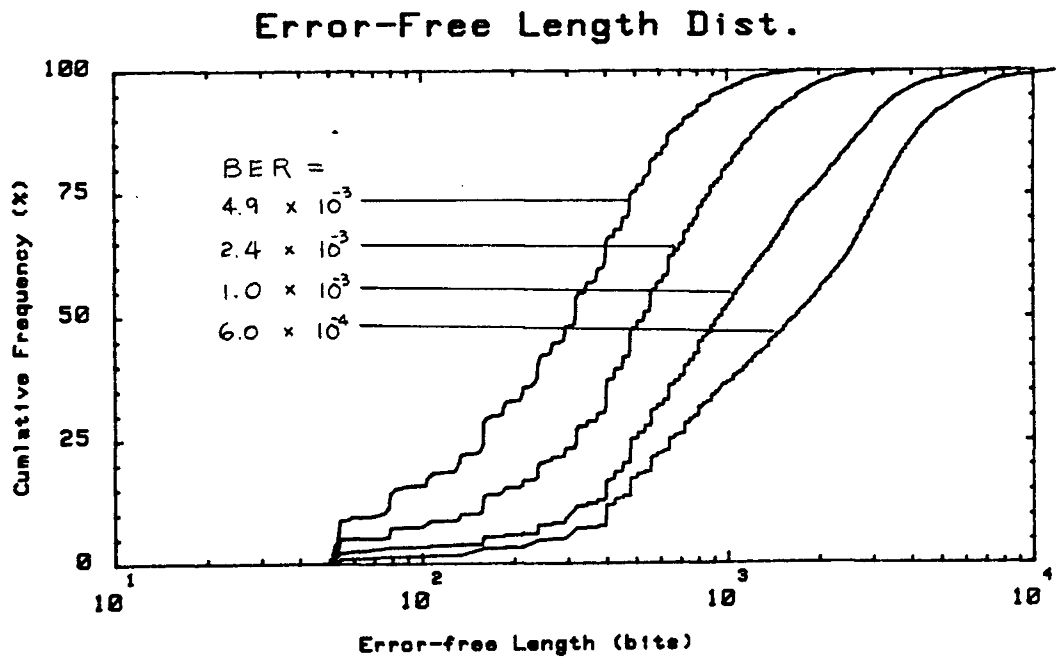
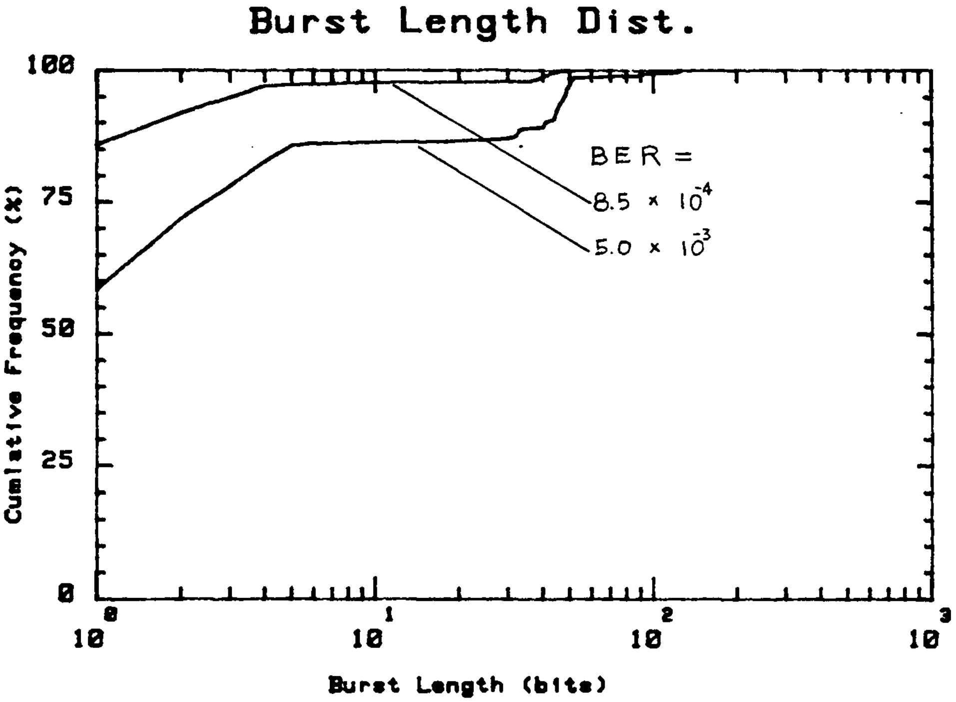


Fig. 4.10 Representative channel error statistics. DS/SSMA-PSK: 4,800bps data rate, 38,400bps code rate, 115KHz carrier frequency. Across-phase transmission.

for which impulse noise was the major cause of errors. Representative error statistics for 1,200bps data rate are presented in Fig. 4.11. The results do not indicate any significant difference when compared with the PSK results in chapter 3.



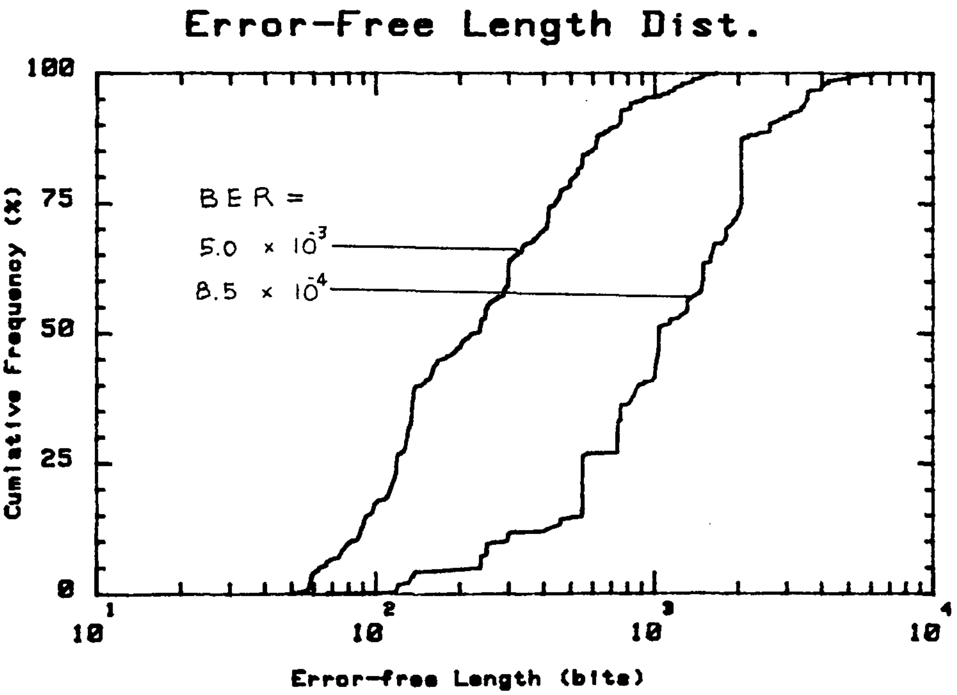


Fig. 4.11 Representative channel error statistics. DS/SSMA-PSK: 1,200bps data rate, 38,400bps code rate, 115KHz carrier frequency. Across-phase transmission.

5. IMPLICATIONS OF THE TEST RESULTS

5.1 Forward Error Correction (FEC) Coding

Under typical channel conditions the measured error statistics indicate that short error bursts comprised a large percentage of the total errors when BER $\cong 10^{-3}$. If FEC coding is employed for error control, a code capable of correcting several random errors or a short error burst would combat a high percentage of all errors encountered. Although burst error correcting codes are less powerful than random error correcting codes, their use may be favoured due to simpler and less expensive decoding (A low-cost modem is desirable). As well, burst error correcting codes have high code rates. As an example, a class of cyclic burst error correcting codes called Fire code [5] can be decoded relatively easy using shift-register circuits. A (105, 94) Fire code which is capable of correcting any single burst of four or less errors has a code rate equal to $94/105 \cong 0.9$.

By properly choosing a suitable code, FEC can significantly improve system performance. However, there will remain some uncorrectable error patterns for handling by other techniques when very high reliability is required.

5.2 Automatic-Repeat-Request (ARQ) Strategies

In many data communications systems, error detection and retransmission schemes are used for error control because these methods are easy to implement and can provide high system reliability. Such schemes are particularly effective when the average channel bit error rate is small. However, the throughput of an automatic-repeat-request (ARQ) error-control system deteriorates quickly as the channel error rate increases. Fig. 5.1 shows the throughput efficiencies of the ideal selective-repeat ARQ (which does not depend on the round-trip delay) and the go-back-N ARQ schemes for a satellite channel with a data rate of 1.5Mbps and a round-trip delay of 700ms. One can see that even for the ideal selective-repeat ARQ, a channel error rate of 10^{-4} is needed to provide acceptable throughput performance.

For high speed data transmission in an impulsive noise environment, system performance can eventually reach an asymtote even though the received SNR continues to increase. Thus, a continual increasing of the transmitter power to reduce BER may not be viable. For example, up to a few watts of transmitter power was needed by the FSK system just to obtain a 10^{-3} BER performance when it operated in the

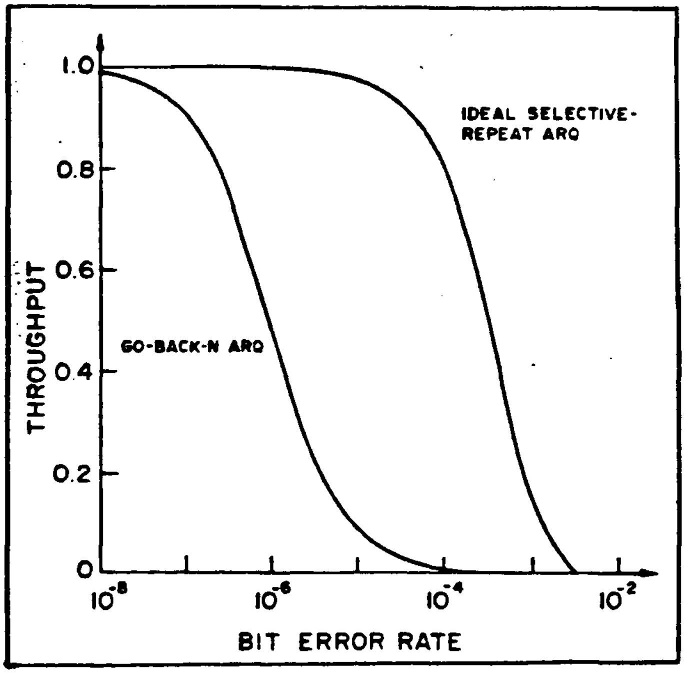


Fig. 5.1 Throughput efficiencies: the ideal selective-repeat ARQ with infinite buffer and the go-back-N ARQ with code block length n = 2024 [23].

industrial building with a data rate of 19,200bps. As a result of the high BER encountered, error-control schemes employing conventional ARQ strategies are not suitable for high speed data transmission, due to the frequent retransmissions of codewords detected in error. This is particularly true if the maximum permissible transmitter power is limited in order to reduce costs or to meet regulatory limitations, such that the system cannot guarantee a small enough channel error rate to maintain a high throughput with ARQ.

At lower data rates (1,200bps or below), impulse noise effects are small, and the system performance follows more closely with the theoretically predicted AWGN result. In addition, a lower data rate means lower transmitted and received signal power for the same BER performance. For example, when the data rate is reduced from 19,200bps to 1,200bps, a reduction of 12dB of received signal power is achieved. At low data rates it becomes practical to use increased transmitter power levels to reduce BER so that simple error control such as conventional ARQ becomes feasible.

5.3 ARQ with FEC Coding

ARQ and FEC schemes can be combined to form a class of error-control strategies commonly referred to as hybrid ARQ [23]. In a straight forward hybrid ARQ system, an error pattern within the correcting power of the designed code will be corrected as with ordinary FEC. However, if the detected error pattern is outside the correcting power of the designed code, the received codeword is rejected and a retransmission is requested, as under ordinary ARQ. This whole process is repeated until a codeword is either interpreted as error-free or successfully corrected. As a result, for a channel with a fairly high BER a hybrid ARQ scheme can increase system throughput above that for an ARQ system alone while increasing system reliability above that of a FEC system alone.

From the above investigation, a proper combination of ARQ and FEC seems to be the most suitable error-control strategy for power line channels. As majority of the error patterns involve short burst errors which can be corrected relatively easily and efficiently. The remaining uncorrectable long error bursts would be handled by retransmission of the errored block.

5.4 Bit Interleaving

As noted earlier, power line channels do occasionally suffer from severe signal fading. If the fading is deep enough, a large number of data bits will be in error resulting in very long error bursts. To counteract this infrequent but existing situation, bit interleaving would be very useful. Bit interleaving combined with hybrid ARQ can provide a very reliable power line data communications system. However, it should be noted that with bit interleaving, a message is essentially received only when all interleaved codewords have been received [22].

From the results of the error statistics measurements in chapter 4, bit interleaving should be able to improve the system performance of the 3 out of 4 majority decision DS/SSMA-FSK system. Because the errors occurred in small bursts, a small degree of interleaving would be adequate to effectively disperse the error bits to achieve better performance. Actual implementation of a short interleaver 31 bits long confirmed the above ideas [24].

5.5 Summary

Based on the measurement results and observations, error correction combined with retransmission is suggested for error control in high speed data communications systems operating on power line channels. The error correcting capability of the code would be designed for raw channel BER = 10^{-3}. However, the system should be designed to operate with a better BER performance because of the margin needed to compensate for the medium to long term channel BER fluctuations. For protection against (relatively uncommon) severe signal fades, bit interleaving could be used to provide additional protection without introducing more redundancy. The 10^{-3} BER value is chosen because better BER performance is more difficult to guarantee, while worse BER performance is not sufficient for maintaining high quality service for many applications.

At lower data rates, BER performance better than 10^{-5} can be guaranteed. With this BER value simple ARQ error control is adequate for high reliability, while more complex schemes such as ARQ with FEC can provide extra high reliability. A good practical example is given by the Nonwire powerline module [25] which supports 1,200bps data rate transmission for in phase transmission (For communications among different phases, a specialized modem having 3 separate power line couplers for sending out signal simultaneously on all three phases is apparently used). Nonwire's specification states: "Error Rate: Better than 10 to the minus 5 single bit error rate" without any error handling. However, with error handling, the specification says: "One undetected data error per 2 years continuous operation, guaranteed by built-in-software error detection and correction logic." The error control used by the Nonwire product is single error correcting Hamming code plus a checksum for error detection and retransmission. The Nonwire modem operates with a very high 8 volt peak-to-peak output signal level at 1,200bps, and power line modems having higher data rate are currently unavailable.

Regardless of the error-control scheme used, the choice of a proper error control code is critical, especially when very good raw BER performance cannot be guaranteed. A proper code can provide good throughput as well as reliable performance. The results obtained from the measured channel error statistics enable intelligent choices to be made for error control codes and protocols. The final decision remains on the hands of the users, for specific applications.

6. TRANSMISSION CHARACTERISTICS OF INTRABUILDING POWER LINE CHANNELS

Unlike many other communication channels which have a relatively flat signal transmission spectrum, the transmission characteristics of intrabuilding power line channels can be highly frequency dependent. A small change in the operating frequency band can result in a large change in received signal strength. A good understanding of the signal spectrum is needed for the efficient system design, to enable least transmitter power for a given BER performance.

Attenuation verses frequency measurements were made on five buildings, including industrial and residential buildings. Most measurements were performed during the time periods of heavy electrical loading, although some measurements were also made during other time periods of a day for comparison purposes.

The effects of some typical consumer loads on signal transmission were investigated. Finally, some comments are made regarding transmission distance within a building's power distribution network.

6.1 The Measurement System

All measurements were performed using the experimental setup shown in Fig. 6.1.

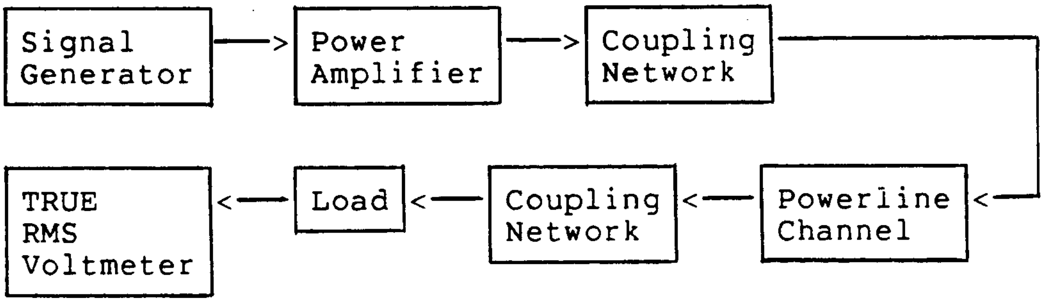


Fig. 6.1 Experimental setup for attenuation measurement.

A single frequency sinusoidal tone is generated and then amplified by the power amplifier and coupled onto the power line through the coupling network. The coupling network is a passive high pass filter having a 3dB cutoff frequency between 20-30KHz. At the receiver, a 10ohm resistor is used as the load.

For a given transmitter voltage, the attenuation is given by

$$\text{Attenuation (dB)} = 10 \log_{10} \frac{V^2rec - V^2noise}{V^2tr}$$

where Vtr is the transmitted voltage measured at the power amplifer output
Vrec is the received voltage measured across the 10ohm load, with transmitter on
Vnoise is the received voltage measured across the 10ohm load, with transmitter off.

All voltage readings were taken using a true RMS voltmeter. Measurements were made at 16 discrete frequencies in the 20KHz to 240KHz range.

6.2 Attenuation Characteristics: Industrial Building

The four storey high industrial building used in the error statistics measurements was used again for studying the signal transmission characteristics of intrabuilding power line channels. Fig. 6.2 shows the attenuation verses frequency characteristics obtained during in phase signal transmission, where the transmitter and receiver were separated by 20-30 feet of the power distribution network inside a room with no specific loadings. Fig. 6.2 shows little variation in signal strength over the frequency band. Although this result is too ideal for any real-life situation, it does provide a comparison for other measurements.

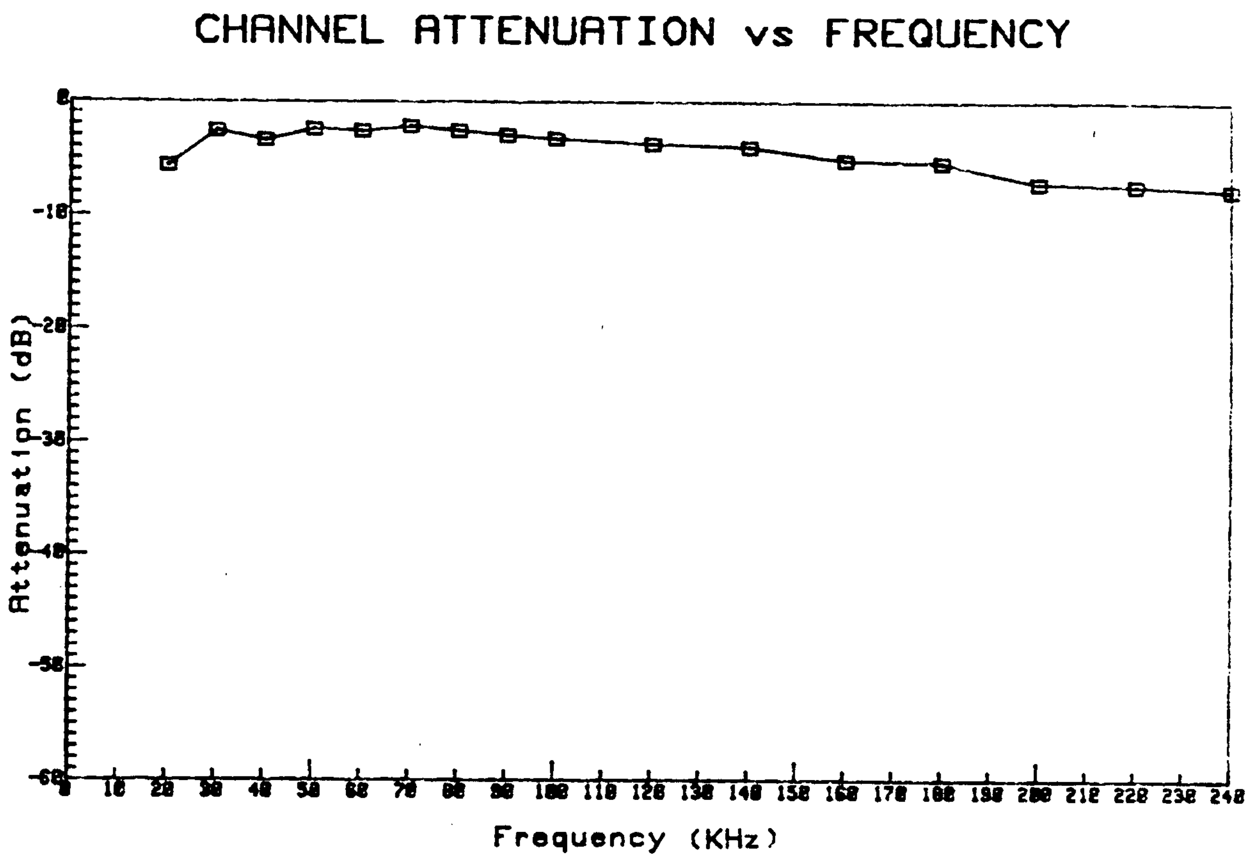


Fig. 6.2 Attenuation vs. frequency characteristics: industrial building. In-phase signal transmission through 20-30 feet of power distribution wiring.

Fig. 6.3 shows the result obtained during in phase signal transmission, where the transmitter and receiver were separated by an unknown length of transmission path. One can see that the channel remains relatively flat below 140KHz, but then starts to roll off very quickly.

Fig. 6.4 shows the results obtained during two across phase signal transmissions. The two curves were obtained with the receiver fixed at one phase, and the transmitter placed at the other two phases different from that of the receiver. Both curves indicate that channel roll off starts at approximately 30KHz. The above measurements were performed during the day between 9 a.m. to 5 p.m..

Comparative studies were done during night time periods (after 7 p.m.). Fig. 6.5 shows the result obtained during in phase signal transmission. In general, the figure is similar to Fig. 6.3 in that rapid channel roll-off begins at around the same frequency range (140-160KHz). The results for across phase signal transmission are shown in Fig. 6.6. Both curves show continuous increase in attenuation as frequency increases. In addition, the curves indicate serious narrow band drop-outs at around 80KHz and 160KHz.

From these results obtained, one sees that the average

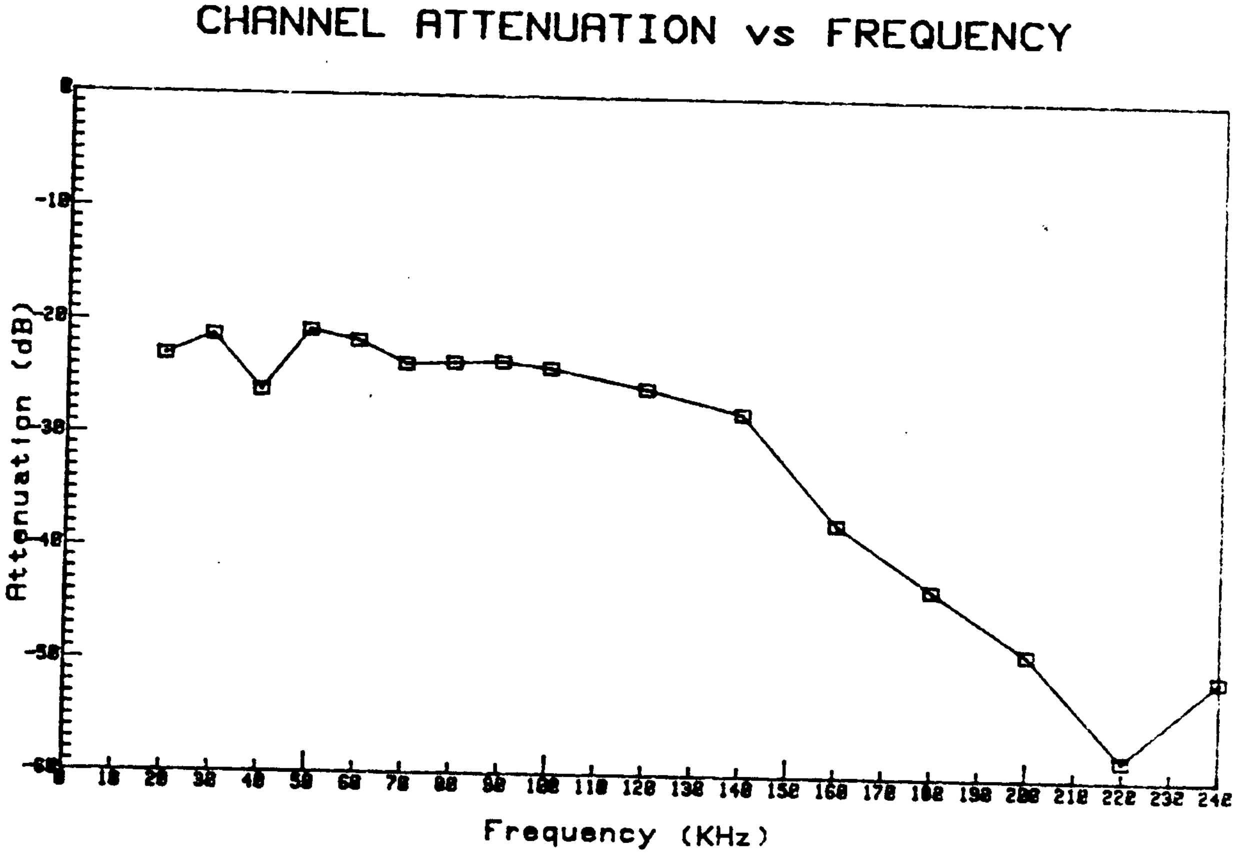


Fig. 6.3 Attenuation vs. frequency characteristics: industrial building. In-phase signal transmission through an unknown path at day time.

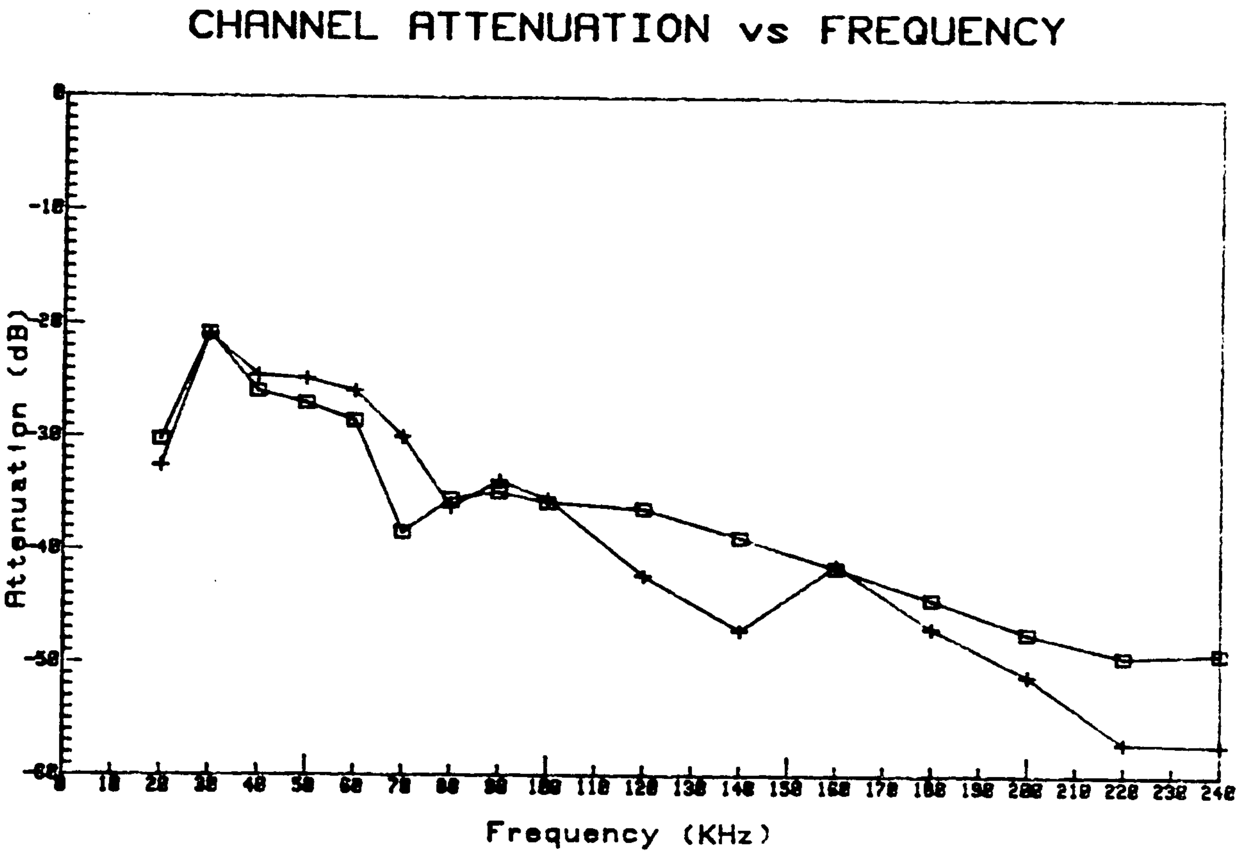


Fig. 6.4 Attenuation vs. frequency characteristics: industrial building. Across-phase signal transmission through unknown paths at day time.

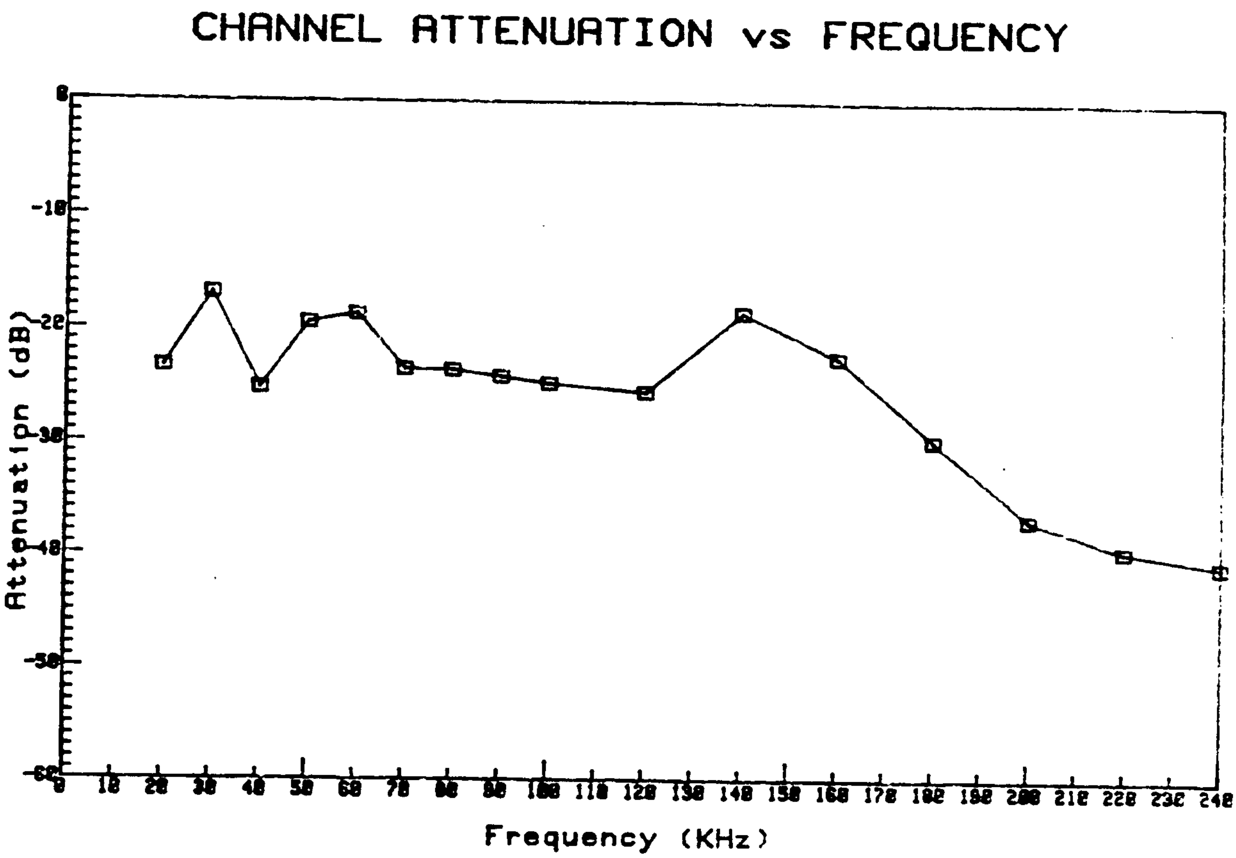


Fig. 6.5 Attenuation vs. frequency characteristics: industrial building. In-phase signal transmission through an unknown path at night time.

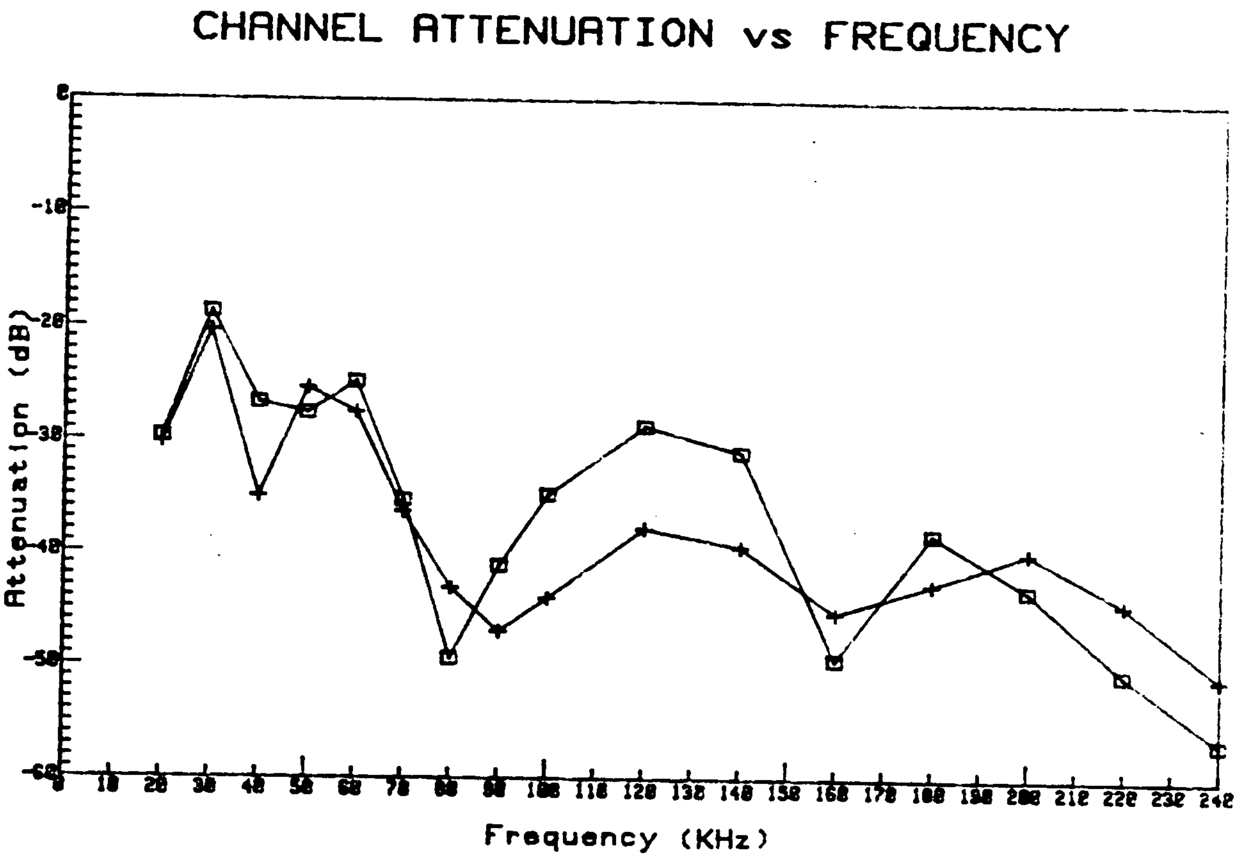


Fig. 6.6 Attenuation vs. frequency characteristics: industrial building. Across-phase signal transmission through unknown paths at night time.

level of attenuation for in phase signal transmission is less than that for across phase signal transmission, especially at high frequencies. Transformers cause strong signal attenuation from one transformer phase to another. As well across phase signal transmission also seems to suffer more easily from narrow band drop-out. Narrow band drop-outs are usually caused by reactive loads, standing waves, reflections and multipath propagation effects on the line [2,4].

6.3 Attenuation Characteristics: Residential Environment

Two apartment complexes, located in two separate residential areas, were used to measure attenuation verses frequency characteristics of intrabuilding power line channels. One building has four floors with approximately 60 individual units; the other is a 12-storey building with more than one hundred individual units. Split-single-phase power is delivered to each building.

Fig. 6.7 shows the attenuation characteristic measured in the low-rise during in phase and off phase signal transmission. Both curves indicate a better transmission medium than in the industrial building. The results presented were recorded from 6-8 p.m..

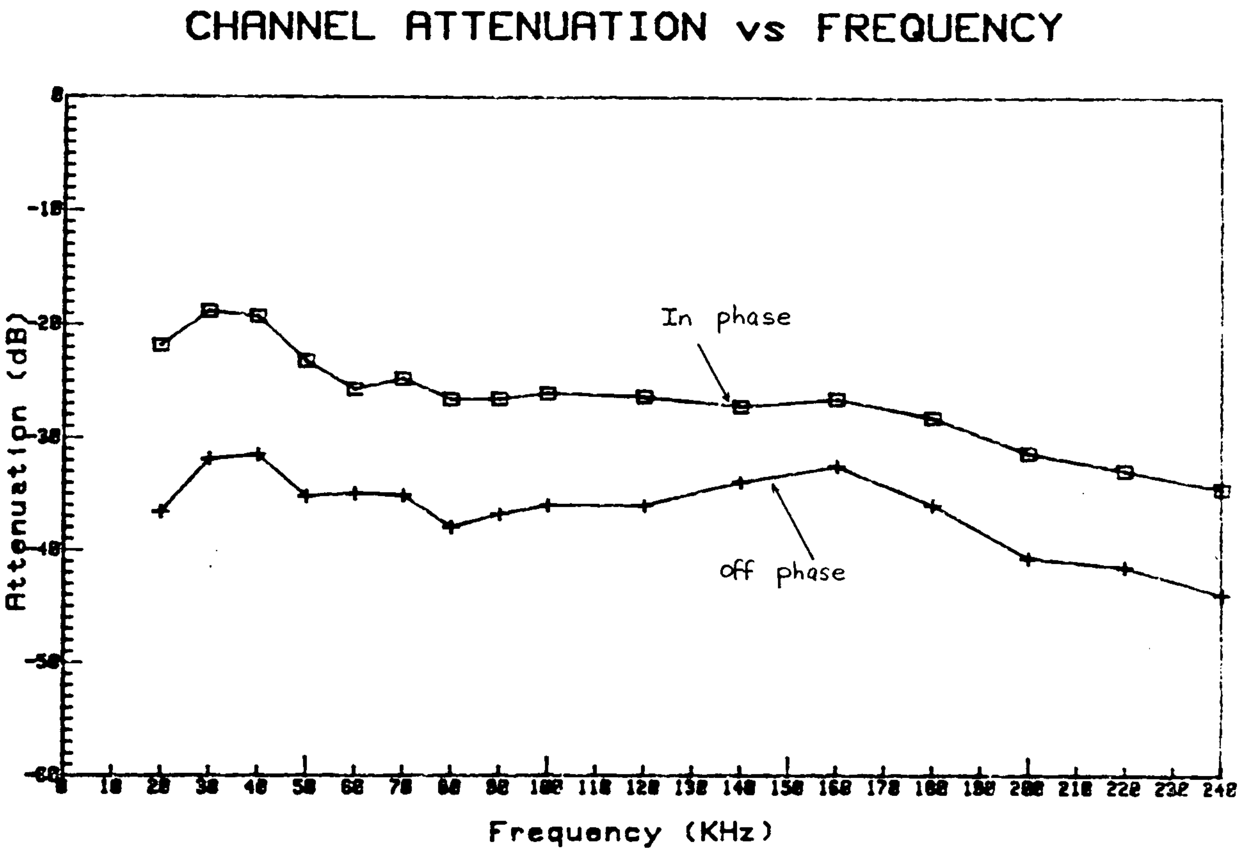


Fig. 6.7 Attenuation vs. frequency characteristics: residential complex (low-rise). In-phase and off-phase signal transmission through unknown paths.

Measurement results obtained in the high-rise building appear in Fig. 6.8 and 6.9. Fig. 6.8 shows the result obtained during in phase signal transmission where the transmitter and receiver were separated by a short transmission path. The measured frequency spectrum is rather flat. Fig. 6.9 shows the result obtained for in phase signal transmission and off phase signal transmission, where the transmitter and receiver were separated by an unknown length of transmission path. These curves indicate that signal attenuation increases rapidly as frequency increases. Again, all results presented were recorded during the 6-8 p.m. time period.

6.4 Attenuation Characteristics: Hospital

A hospital located in downtown Vancouver, B.C. was used to measure the attenuation verses frequency characteristics. Three phase power is supplied directly to the building.

Fig. 6.10 shows the result obtained during in phase signal transmission. The exact signal path between the transceiver was unknown. The curve indicates the beginning of increasing channel roll off at around 140KHz, consistent with what was observed under comparable environment as illustrated in Fig. 6.3.

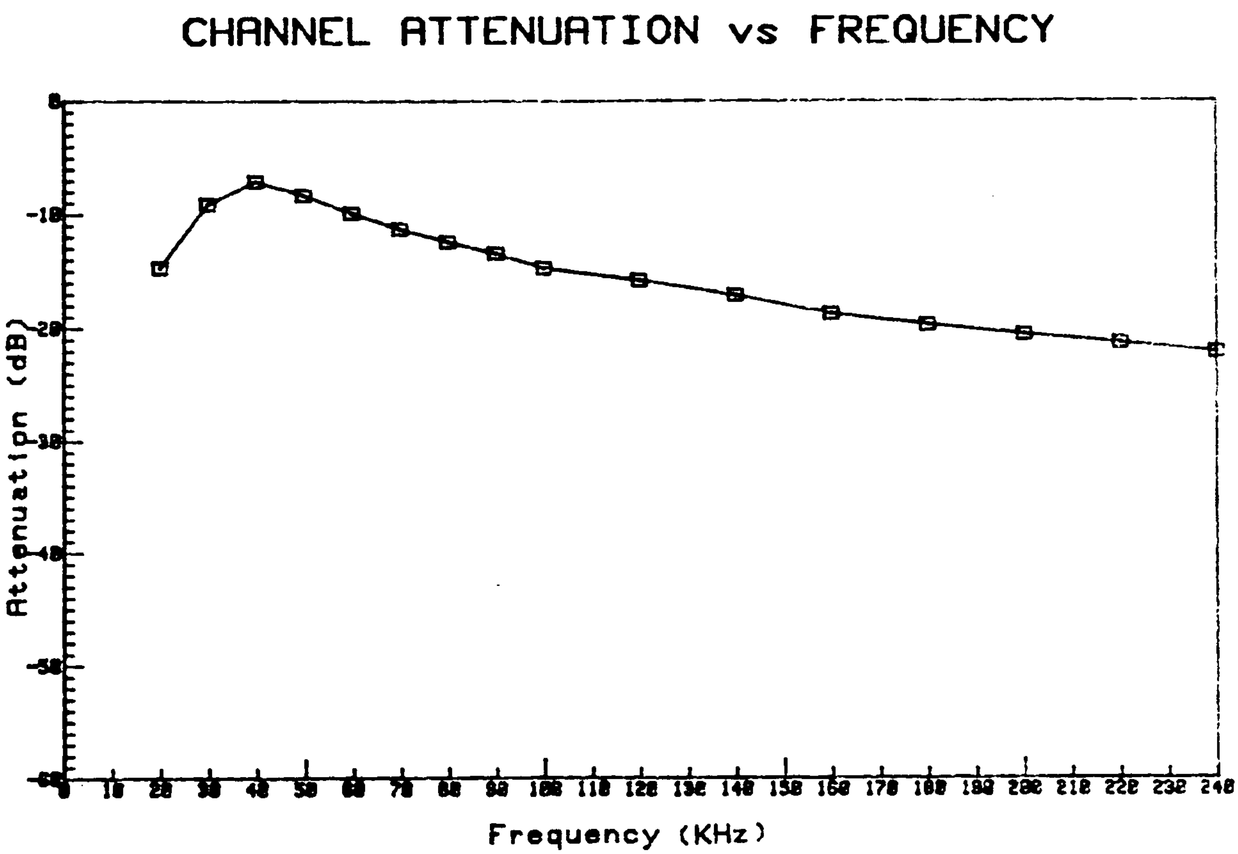


Fig. 6.8 Attenuation vs. frequency characteristics: residential complex (high-rise). In-phase signal transmission through a short path.

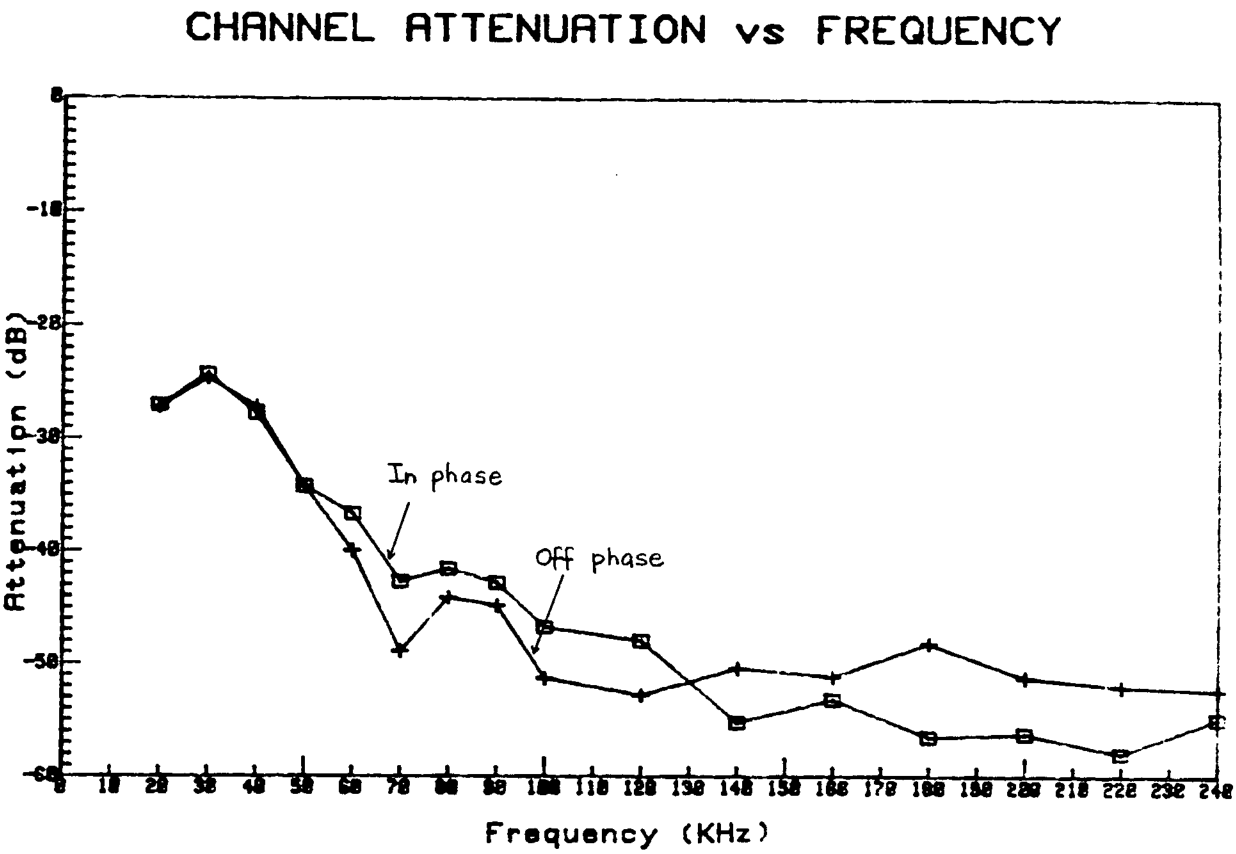


Fig. 6.9 Attenuation vs. frequency characteristics: residential complex (high-rise). In-phase signal transmssion through unknown paths.

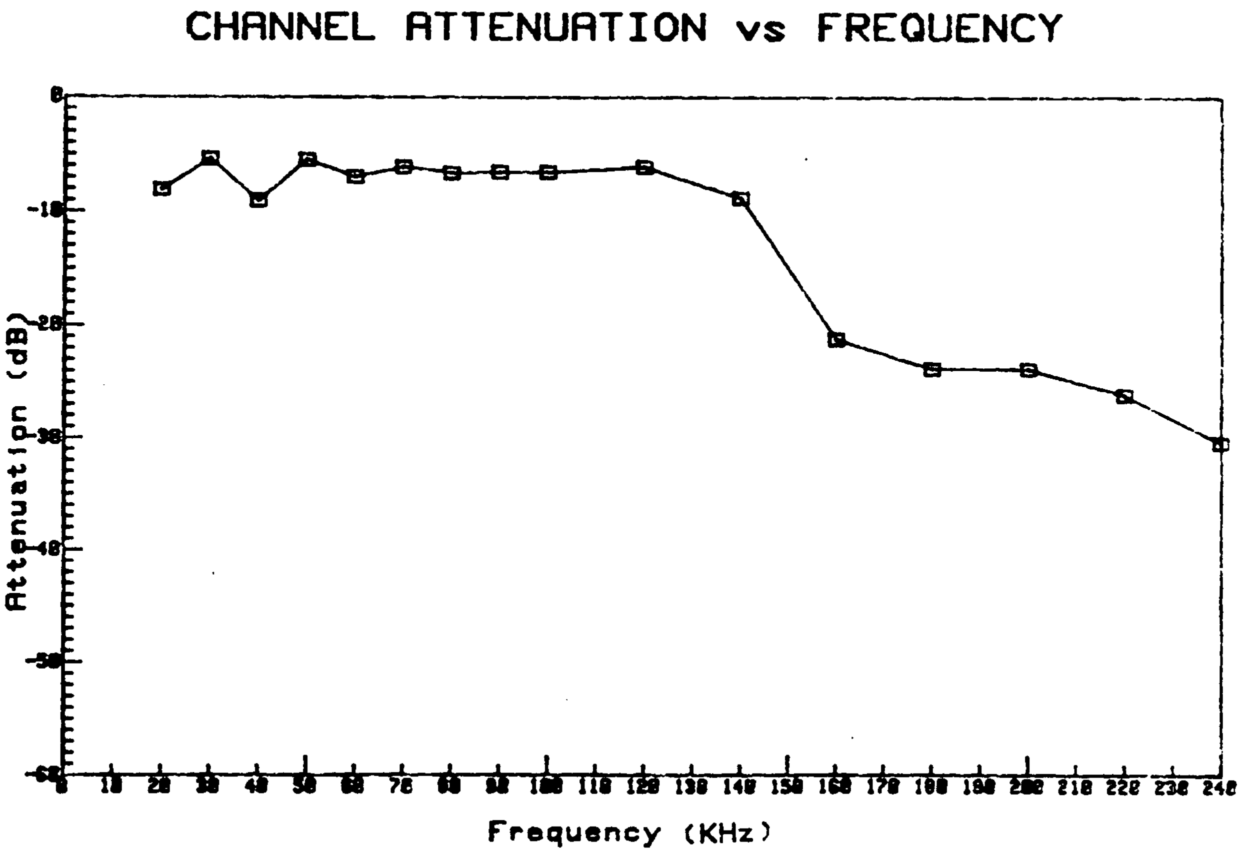


Fig. 6.10 Attenuation vs. frequency characteristics: hospital. In-phase signal transmission through an unknown path.

Figure 6.11 shows the attenuation characteristics obtained for across phase signal transmission. The receiver was fixed at one phase, the transmitter was placed at the other 2 phases different from the one that the receiver was on. One signal path shows greater attenuation than the other, especially at frequencies above 100KHz.

6.5 Effects of External Loading On Signal Transmission

Observations made during the course of previous measurements indicated that the channel transmission characteristics depended on what external loads switched onto the line. This observation motivated a study to determine the effect of some common household appliances on signal transmission. The measurements were conducted in a single family house under controlled conditions. The house is a typical single family residence, where in North America general purpose branch circuits carry 110-volt power to switched lights and plug-in recepticles, and special circuits carry 220-volt power to heavy appliances including clothes dryers, electric ranges and water heater. The attenuation verses frequency characteristic was first determined without specific loads being energized. Thereafter, individual

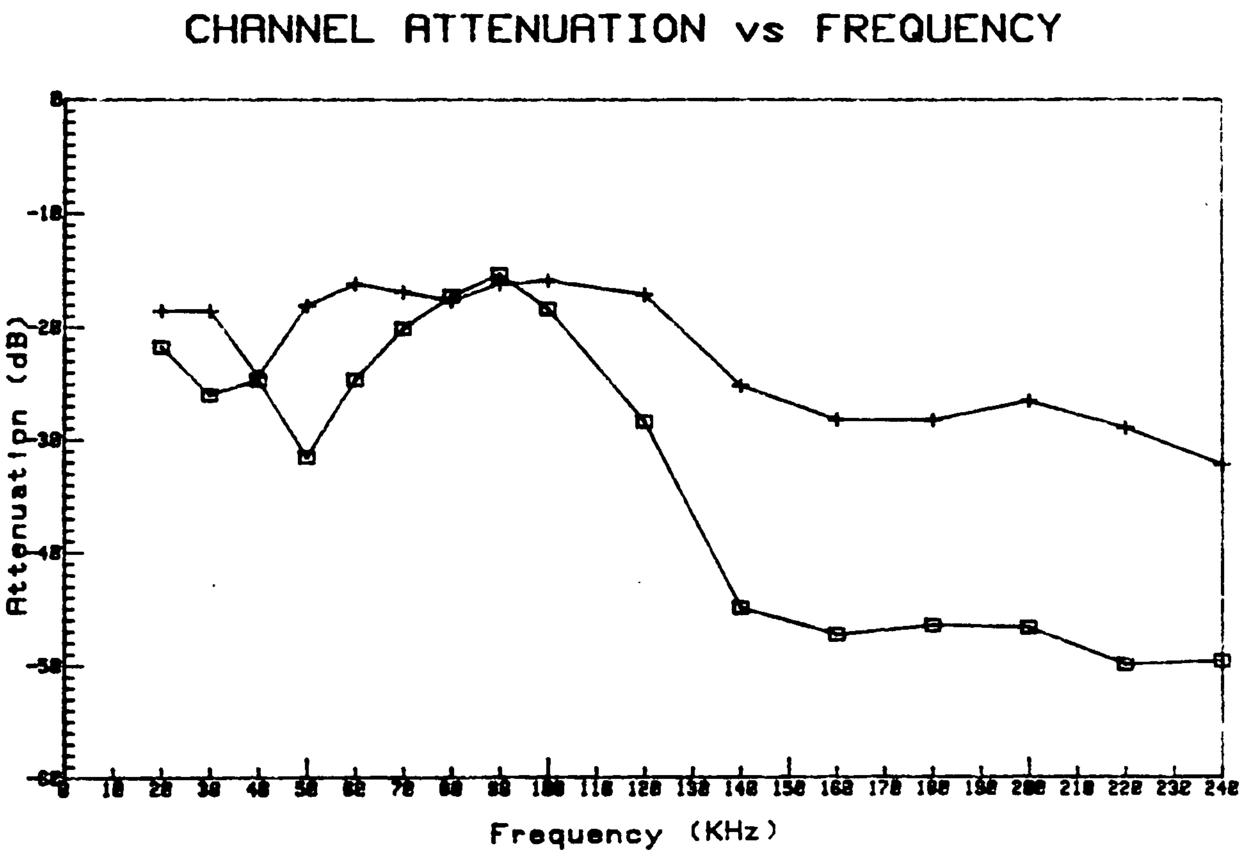


Fig. 6.11 Attenuation vs. frequency characteristics: hospital. Across-phase signal transmission through unknown paths.

consumer loads were placed on the same phase as the receiver then energized.

Fig. 6.12 shows the results obtained for in phase and off phase signal transmission without any specific loading. Then two discrete frequency tones at 50 and 100KHz were used as test signals to identify which consumer load would influence signal transmission. A radio, cassette recorder, vaccum cleaner, razor, sewing machine, fan and flourescent lamp were found to have no effect on the level of signal strength received during in phase signal transmission test. An electric range and a clothes dryer were found to slightly attenuate the received signal level, while a 3KW water heater and TV receiver were found to attenuate the received signal level more significantly.

The effects of the water heater and TV receiver on signal transmission are presented in Fig. 6.13. For the television receiver, it was found that faster roll off of high frequencies occurred. For the water heater, a constant drop of received signal level was observed over the entire frequency band measured.

The tests were repeated for off phase signal transmission. Results similar to those above were obtained

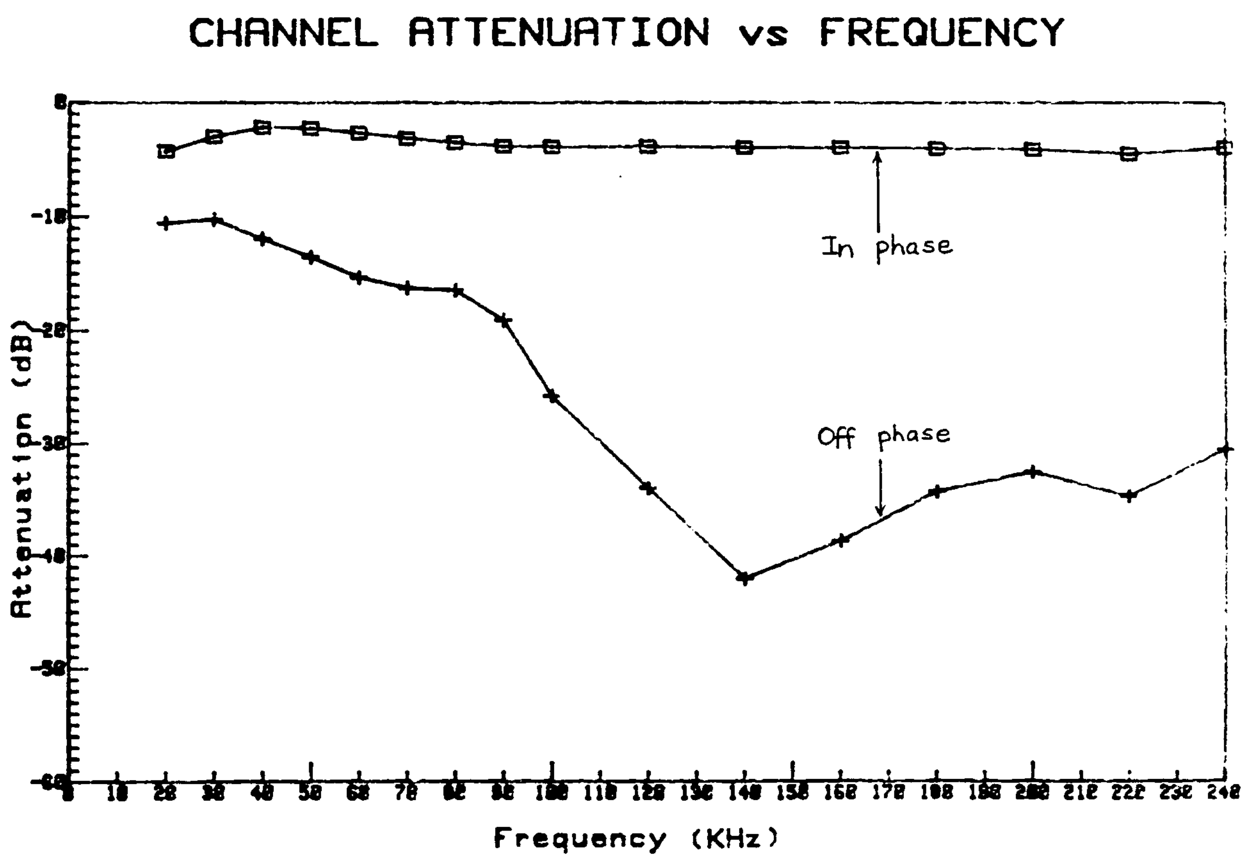


Fig. 6.12 Attenuation vs. frequency characteristics: single family home. In-phase and off-phase signal transmission without specific loading switched on.

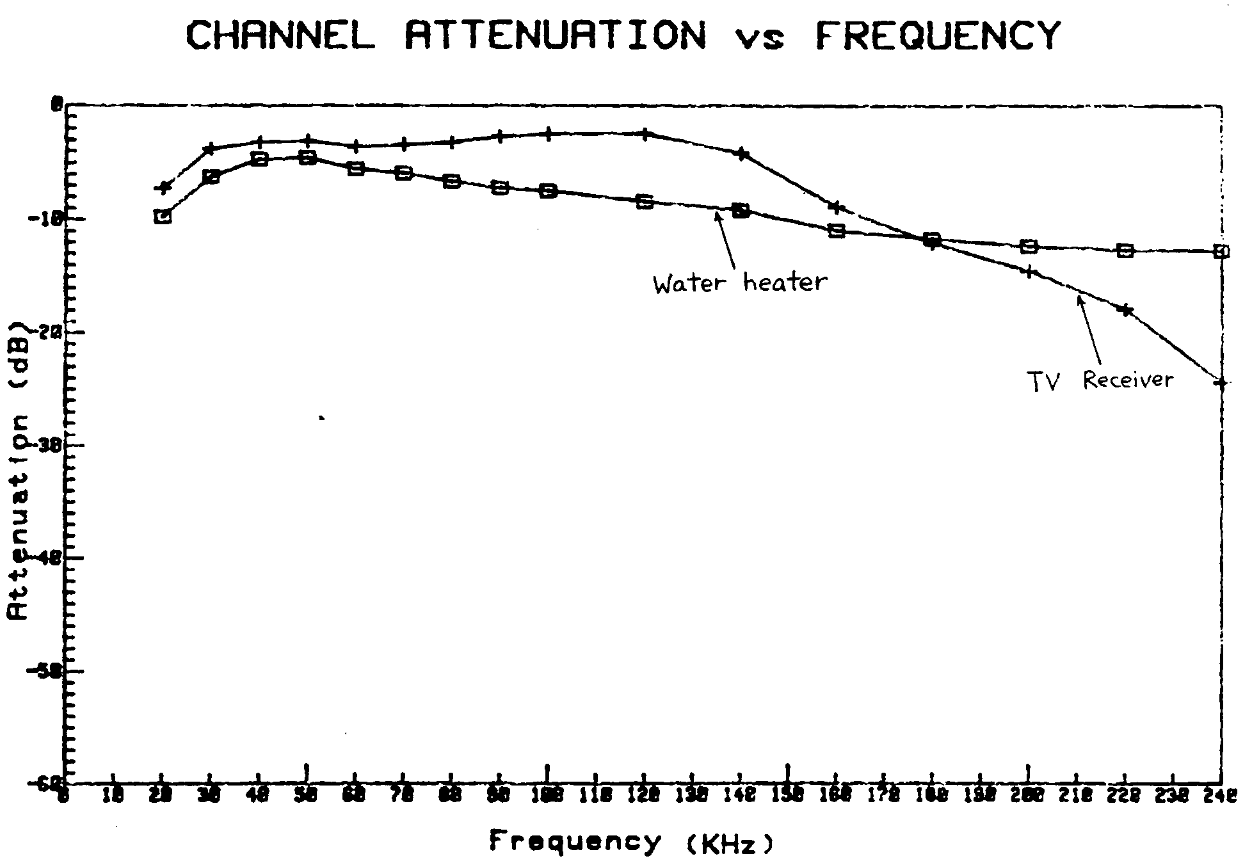


Fig. 6.13 Attenuation vs. frequency characteristics: In-phase signal transmission with water heater and TV receiver switched on.

with two exceptions given by the electric range and clothes dryer. These two appliances improved rather than degraded signal transmission so that signal reception by the receiver was enhanced as shown in Fig. 6.14. These appliances connect across two phases (240 volts) of the supply circuit, and provide a direct path for signal transmission from one phase to another without passing through the lossy transformer secondary. This result definitely suggests the usefulness of installing high frequency bypass capacitors across the different phases (legs) of the distribution transformer to enhance signal transmission between different phases. Similarly, high frequency bypass capacitors installed to connect transformer's primary and secondary would improve signal transmission through distribution transformers for power line carrier applications; without bypass capacitors primary-to-secondary transmission is feasible only below 10KHz.

6.6 Comments on Transmission Distance

A common misconception is that two electrical outlets physically close to each other are separated by a short (good) transmission path. However, this is not always true. If the exact wiring plan of a building is not available, one

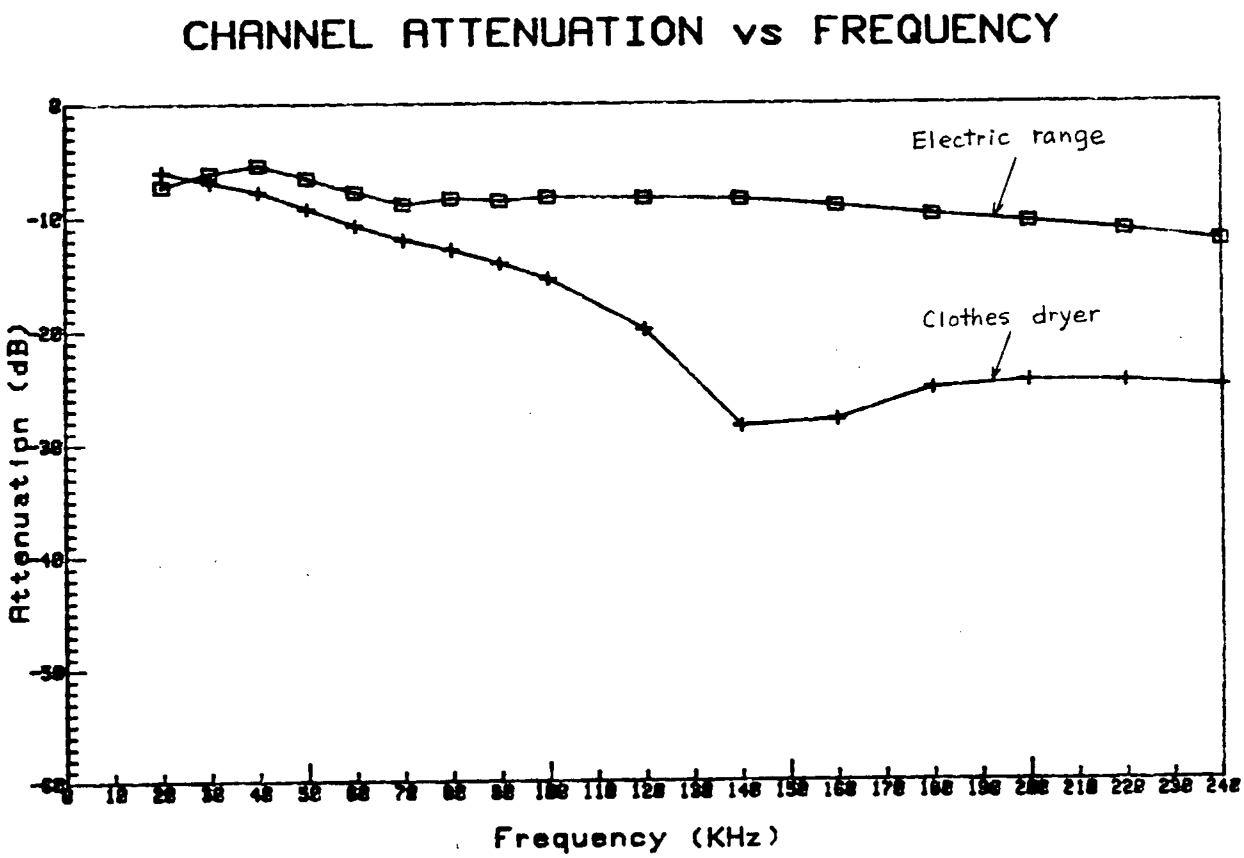


Fig. 6.14 Attenuation vs. frequency characteristics: single family home. Off-phase signal transmission with electric range and clothes dryer switched on.

is generally unable to determine the transmission distance between two electrical outlets. A transmitter and receiver operating on the same floor may be separated by a longer electrical path than when they are located at different floors.

6.7 Summary

The series of test measurements provide improved understanding of signal transmission through power line channels. The measurement data indicates some portions of the frequency spectrum possess better transmission characteristics than others. However, it should be noted that the choice of a good frequency band is a compromise based on both the transmission characteristics and noise levels, and not either characteristic alone.

The transmission characteristics are strongly affected by the loading on the transformer's secondary, and the measurements performed are not intended to cover all possible situations. The results do illustrate typical behaviour exhibited by the transmission medium. When combined with the noise characteristics such data is useful as a first step for choosing signal transmission frequencies.

In addition, the measurement results suggest that high frequency bypass networks can provide a simple way to reduce the heavy transmission losses between phases.

7. CONCLUSION

7.1 Concluding Remarks

The primary purpose of this thesis is to present for the first time error patterns statistics of intrabuilding power line communication channels. These statistics are based on actual measurements on a number of real channels. The results will be very useful for choosing efficient and reliable error control codes and protocols which are essential for reliable communications, and for predicting performance.

The emphasis is on high speed (19,200bps) data transmission where channel bit error rate performance is such that error control coding is essential. As well, high speed communications is desirable for an increasing number of applications. When a large number of users have to share the channel, a high speed channel increases the throughput of various channel multiple access schemes including CSMA and CSMA-CD which are commonly used in packet switched data communications. In these schemes the packet collision probability decreases (assumming a fixed number of bits/packet) as the data rate increases, provided channel errors are not too severe. These multiple-access schemes are very suitable for short delay channels such as the power line circuits being investigated in this thesis.

The results of the error pattern statistical analysis are summarized below:

(1) For normally conditioned channels, impulsive noise is the limiting disturbance in high speed transmission, when the data bit duration approaches the duration of the impulsive disturbance. Depending on its strength and width, an impulse spike or several impulse spikes close together can cause from no error to several errors.

(2) As BER is decreased, the trend is to shorter error bursts, and conversely.

(3) Errors from impulse noise impairment are mostly periodic, since most impulse spikes themselves occur periodically according to the periodic 60Hz power line voltage.

(4) The error pattern behaviour of power line channels is found to be relatively insentitive to modulation schemes and operating frequency. This result occurs because impulse noise is the primary cause of

errors.

(5) Fading is also a cause of errors in power line channels. A deep fade can cause error bursts longer than 100 bits. A weak fade allows weaker impulses which are not normally strong enough to cause an error, to become the cause of an error. Power line fading is periodic with frequency at twice the power voltage frequency or its submultiples.

(6) Based on the measurement results, ARQ with FEC is suggested for error control at high data rates. Burst error correcting codes can be used to reduce decoder cost and complexity, with some sacrifices in performance. Finally, bit-interleaving is proposed for additional protection against momentary decrease in system performance.

(7) At lower data rates (1,200bps or below), impulse noise effects are relatively small. It becomes feasible at these data rates to use more transmitter power to guarantee a better BER performance, and error control becomes relatively easy.

(8) Reliable data communication on intrabuilding electric power lines appears viable, given proper

error control design, even for high speed transmission.

The attenuation characteristics measurements performed on various power line channels lead to the following conclusions:

(1) Average attenuation is generally large, typically in excess of 20dB
(2) Attenuation is frequency selective
(3) Usable bandwidth is limited which also implies that frequency division multiplexing is often impractical
(4) Average attenuation is normally less for in phase than across phase signal transmission
(5) Attenuation can be very dependent on electrical load profile which is time varing
(6) High frequency bypass networks can significantly improve signal transmission involving different phases.

In summary, this thesis enables a much improved understanding of the behaviour and use of intrabuilding power distribution circuits for communications.

7.2 Suggestions for Future Work

Based on the measurement results, models could be developed to characterize the power line channel. From these models, one should be able to derive the error statistics having good agreement with experimental results. However, it will probably be extremely difficult to construct a model which is detailed enough to have general validity.

Other useful work includes tests with actual FEC/ARQ error control strategies at high data rates, tests with simple error control schemes at lower data rates, and examination of ways to reduce losses for across phase transmission.

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