TRANSMISSION OF IMAGE DATA OVER DIGITAL NETWORKS INVOLVING MOBILE TERMINALS

RAKIB SALAHALDEN JALAL, BSc(Eng), MSc

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THE UNIVERSITY OF ASTON IN BIRMINGHAM

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BY
RAKIB SALAHALDEN JALAL

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SUMMARY

There is a growing demand for data transmission over digital networks involving mobile terminals. An important class of data required for transmission over mobile terminals is image information such as street maps, floor plans and identikit images. This sort of transmission is of particular interest to the service industries such as the Police force, Fire brigade, medical services and other services. These services cannot be applied directly to mobile terminals because of the limited capacity of the mobile channels and the transmission errors caused by the multipath (Rayleigh) fading.

In this research, transmission of line diagram images such as floor plans and street maps, over digital networks involving mobile terminals at transmission rates of 2400 bits/s and 4800 bits/s have been studied. A low bit-rate source encoding technique using geometric codes is found to be suitable to represent line diagram images. In geometric encoding, the amount of data required to represent or store the line diagram images is proportional to the image detail. Thus a simple line diagram image would require a small amount of data. To study the effect of transmission errors due to mobile channels on the transmitted images, error sources (error files), which represent mobile channels under different conditions, have been produced using channel modelling techniques. Satisfactory models of the mobile channel have been obtained when compared to the field test measurements.

Subjective performance tests have been carried out to evaluate the quality and usefulness of the received line diagram images under various mobile channel conditions. The effect of mobile transmission errors on the quality of the received images has been determined. To improve the quality of the received images under various mobile channel conditions, forward error correcting codes (FEC) with interleaving and automatic repeat request (ARQ) schemes have been proposed. The performance of the error control codes have been evaluated under various mobile channel conditions. It has been shown that a FEC code with interleaving can be used effectively to improve the quality of the received images under normal and severe mobile channel conditions. Under normal channel conditions, similar results have been obtained when using ARQ schemes. However, under severe mobile channel conditions, the FEC code with interleaving shows better performance.

Keywords

Digital communication systems, Low bit-rate graphic images, Mobile radio, Channel modelling, Error control techniques.

DEDICATED TO

My Wife and Children

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CHAPTER 1

INTRODUCTION

1.1 General

Interest in data communication networks has risen dramatically recently due to the tremendous impact of computers on society. A data communication network is used to connect together a number of computers and terminals. The network exists to transfer and exchange data between computers and terminals. The day-to-day transactions at department stores, banks, offices, and many other public businesses are all dependent upon data networks. This trend is accelerating as more businesses discover the power of computers and communications networks. Data terminals are connected to each other and to host computers via a range of data communication networks. These are; data transmission via the public switched telephone network (PSTN), data transmission over wide-area networks using packet-switched techniques and data transmission over local area networks (LANs) provided within an office, factory or university complex. The most common types of traffic handled over data networks are interactive data, transmitted in short bursts of a few bytes to about 1 kbytes, between terminals or between terminals and computers. Networks can also handle file transfers involving the transmission of up to millions of bytes between mainframe computers. Videotex images, facsimile, videoconference and television images are also being considered for transmission.

A recent extension of the telephone facility to mobile terminals has taken place with the introduction of cellular mobile radio telephony. Mobile radio communication systems designed for analogue voice communication have been very successful. There is now growing interest in extending the mobile channel to incorporate both voice and a new range of services similar to those used over the conventional data communication networks mentioned above. There is therefore a significant demand for mobile data terminals. This development can be achieved by extending the data transmission networks listed above to incorporate mobile data terminals. The communication path in this case includes a PSTN, a packet-switched network, or a local area network provided within an office complex or university campus in combination with a mobile data terminal. Several systems have been proposed for data transmission in mobile channels, for example, data transmission over the Total Access Communications System (TACS) cellular telephone system used in Great Britain. Moreover, the great success of mobile radio systems in their analogue form has increased the demand for the introduction of digital mobile radio, such as the pan-European digital cellular mobile network, which is planned to be in operation in the near future.

1.2 The Aims of the Research

Communication networks incorporating mobile data terminals were initially concerned with the exchange of data information such as text and numbers between computers and terminals. However, very recently there has been an increasing demand for the exchange of image data over mobile terminals. Because users are trying to exchange information and not just data (words and numbers), and because images convey extensive information much more efficiently than words and numbers, transmission of image data over mobile terminals will play an important role in the future of telecommunications. For example, in the planned pan-European digital mobile network, services involving the transmission of both voice and image data are considered. This study is concerned with the transmission of image data consisting of basic line diagram graphic images over digital networks involving mobile terminals.

The reason why transmission of image data over mobile terminals will increase is that large amounts of data information are being held in data bases in mainframe computers in the form of text, numbers or images. This is particularly the case for service industries such as the Police force, Fire brigade, the medical services and other emergency service operations, which make extensive use of computers at their headquarters. The need to access this information directly from a mobile terminal is of major importance to these services. For example, with the wide-spread use of computer graphics, line diagram images such as street maps, building plans etc. can now easily be stored in computer files, ready for immediate access in an emergency to the mobile users of public services such as Fire brigade, the Police force, the Gas or the Electricity services. These line diagram images can be updated and can be available quickly using modern techniques in computer graphics systems.

This sort of service can be easily accommodated within conventional data communication networks which have adequate transmission rates and low probability of transmission errors. However, these services cannot be applied directly to mobile terminals for two major reasons.

1. It is to be expected that rates of digital transmission over mobile radio channels will be low compared to those available over conventional networks. In general, images based on a full pixel representation and with several intensity levels for each pixel, such as image information of a television quality or video conference pictures, require a large amount of data for storage or transmission. For example, a typical image with a resolution of 512x512 pixels and with 8 bits/pixel intensity requires a transmission capacity of 512x512x8 = 2.097 Mbits. This is a large transmission capacity for a communication network with a limited bandwidth. Full duplex modems with transmission rates of 1200, 2400 and 4800 bits/s are nowadays commonly used for data transmission over the cellular radio system. Using a modem at 2400 bits/s, such an image would take almost 15 minutes to transmit. Obviously this time is so long that it would be unreasonable to transmit such images over such a limited bandwidth network. It is unlikely that adequate transmission rates will be available in mobile channels that will make it possible to transmit such images. Some method of transmitting basic image information that requires low bit-rates is therefore required. For emergency services, basic line diagram images such as street maps, building plans and similar line diagrams represent a significant range of interest. Methods of transmitting line diagram images with low bit-rates are therefore considered in this study.

2. Mobile channels differ from conventional digital communication channels in that the received signal suffers from multipath (Rayleigh) fading. Rayleigh fading is a phenomenon caused by the simultaneous reception at the antenna of electromagnetic waves which have travelled through slightly different path lengths due to reflection from various static or moving objects. This causes the received signal to be variable in strength and frequently to fall below the acceptable threshold level at the receiver. It is generally accepted that the mobile channel is a poor communication channel in terms of transmission errors, which usually occur in bursts. The length of these error bursts depends on various mobile channel parameters. In conventional communication networks, such as the PSTN, burst and random errors predominate, with probability of error rates which are much lower than in mobile channels. It is to be expected that a system that works acceptably well over a mobile channel should give good performance when used over conventional communication networks such as the PSTN. To transmit data over mobile channels with acceptable performance and error rates at the receiver, powerful error protection techniques must be used. Forward error correcting codes (FEC) with interleaving or automatic repeat request techniques (ARQ) are common methods in mobile channel encoding.

1.3 The Approach Followed in the Research

The main purpose of this research is to transmit line diagram images with an acceptable quality, a reasonable transmission time and using a simple approach as much as possible, over digital networks involving mobile terminals at transmission rates of 2400 and 4800 bits/s. The system described in this thesis uses a low bit-rate source code for representing line diagram images. The encoded line diagram test images are subjected to different mobile channel conditions. The performance results of the received line diagram images subjected to mobile transmission errors are evaluated subjectively with and without channel coding techniques. The rest of this section gives a brief outline of the approach followed in this research programme.

A low bit-rate source encoding technique is proposed to represent line diagram images. Two line diagram images (the 4th floor north-wing plan at Aston University and the Aston University campus map) are selected as typical of test images which may be useful for many mobile users. In order to represent the line diagram test images with as small amount of data as possible a low bit-rate source code based on geometric code is proposed rather than a pixel based code. Geometric encoding uses drawing instructions such as Line, Marker, Polygon, Rectangle and Text to represent line diagram graphic images. For example, a straight line is specified by a plot line command and the coordinates of its end points. This is a much more natural and concise way of describing a diagram than scanning it on a pixel basis. This approach has been adopted in many computer graphics systems and videotex systems. In geometric coding, the amount of data required to represent a line diagram image is related to the image content. A simple map would therefore require a smaller amount of data than would a map containing more detail. This is an important feature, as simple graphic images would require a small amount of data for storage and consequently a short transmission time could be achieved.

Transmission errors due to the effect of mobile channels on the transmitted line diagram images can have serious consequences. This is because of the generally poor quality of mobile channels, as mentioned earlier. Moreover, the effect of transmission errors also depends on the type of transmitted information. For example, the effect of transmission errors on the telephony service in the existing cellular mobile radio network is minor because of the inherent redundancy in speech. The effect of transmission errors on mobile data transmission is more severe because, in general, there is little or no redundancy in most applications. Line diagram images represented by geometric codes are expected to be sensitive to transmission errors because they represent line diagram images in an efficient way. For example, transmission errors could change the coordinates of a straight line, which may be a very misleading error. To investigate the effect of transmission errors due to mobile channels on the transmitted data of the line diagram test images, an error source that represents the mobile channel is required. A channel model is proposed to generate the error source (error files) under various mobile radio channel conditions.

The quality of the transmitted line diagram images over mobile channels is obtained under various mobile channel conditions. Subjective performance tests are proposed to evaluate the quality of the received line diagram test images. To overcome the effect of transmission errors due to mobile channels on the received line diagram images, several error protection codes are proposed. The aim is to obtain a suitable error control code to protect the image data such that the reproduced line diagram images will be acceptable to the users under adverse mobile channel conditions. The performance of the transmitted line diagram images is evaluated using the selected error protection codes.

1.4 Outline of the Thesis

This chapter has described the reasons why this work was carried out. A brief description of the proposed system has also been given.

The second chapter of this thesis reviews some of the published literature in the field. After describing the various types of digital data communication networks, the transmission of image data over such networks is considered. The requirement to transmit image data over digital networks involving mobile terminals is discussed. The chapter then deals with the limitation of mobile channels, followed by a discussion of recent approaches for the transmission of data and low bit-rate image data over mobile channels.

The first part of chapter 3 presents low bit-rate image data used in communication systems such as facsimile and videotex systems. In the next part of this chapter the proposed low bit-rate source encoding based on geometric encoding used for representing line diagram graphic images is given. Finally, the data format of the geometric drawing instructions to be used for representing the line diagram test images is given.

Chapter 4 is concerned with the modelling of the mobile radio channel. The characteristics and behaviors of the mobile radio channel are discussed. The approach used for modelling the mobile radio channel using computer simulation is then given in detail. Finally, the results of the channel modelling are used to evaluate the error statistics of the mobile channels such as channel bit-error rate, error-free gap distributions, burst distributions and block error statistics.

The results of the channel modelling are then used to evaluate the influence of errors on the quality of the transmitted line diagram test images. Chapter 5 deals with the transmission of the unprotected line diagram test images to mobile channels. The first part of the chapter details the effect of errors deliberately added on various bits of the graphical geometric and text elements. A receiver protocol is developed to process and reproduce the received test images when corrupted with transmission errors. The subjective performance test results of the unprotected line diagram test images subjected to mobile transmission errors are given. The results are shown for various mobile channel conditions.

The results obtained from chapter 5 show that channel error protection schemes are required to ensure good quality for the received images. Chapter 6 is therefore devoted to the description of various error control techniques used in digital communication systems. The first part of the chapter deals with forward error correction techniques (FEC). After presenting the fundamentals of linear block and binary cyclic codes, attention is concentrated on majority-logic decodable codes which are comparatively easily decoded. Interleaving techniques, commonly used in combination with forward error correcting codes in bursty channels such as mobile channels, are also discussed. The second part of the chapter is devoted to the general description and the performance of automatic repeat request techniques (ARQ).

Chapter 7 deals with the transmission of line diagram images to mobile channels using FEC with interleaving and ARQ error protection techniques. The first part of the chapter deals with the performance evaluation of the proposed FEC codes with interleaving. The code with interleaving which shows comparatively good performance results under various mobile channel conditions is then used for protecting the transmitted test images. The subjective performance results of the test images are then given. The second part of the chapter is concerned with performance results of the transmitted line diagram test images using the ARQ schemes.

Finally, chapter 8 summarises and discusses the main results of the research, together with suggestions for further work.

CHAPTER 2

REVIEW

2.1 Digital Data Communication Networks

Data communication forms a substantial part of the modern telecommunication business. In general, data communication is concerned with the processing and communication of digitally encoded information between distributed computer systems and terminal systems. A computer system can be any size from a large main-frame computer to a mini-computer system. Terminal systems can take many physical forms, but the majority provide a user with a keyboard for the input of data to the computer and a visual display unit or printer for the presentation of data output from the computer.

A data communication network is used to connect together a number of geographically separated computer systems and terminal systems for the exchange of data. The communication network may be made up of a large number of terminals physically distributed over a wide geographical area and communicating with a large centralized computing complex. Alternatively, a network may comprise a number of terminals physically distributed around a single block of offices and communicating with a central computer located in the same block. A communication network may also consist of a number of computer-based office equipments in a single block of offices providing , for example, word processing functions and access to various shared resources, such as printers, copiers ... etc. [1]. In this respect the communication networks concerned include all types of wired link networks such as telephone lines, coaxial cables and glass fibre.

Within the data communication networks, the term data is normally reserved for describing a set or block of one or more digitally encoded alphabetic and numerical characters being exchanged between computers or between terminals and a central computer. The most common types of data handled over communication networks are interactive data, generally transmitted in short bursts of a few characters between terminals and computers, file transfer, involving the transmission of much higher numbers of characters between computers, or between mass storage systems [2]. The efficient transmission of data between computer systems, or between terminals and a central computer, is considered to be an important function in the field of data communication networks.

The earliest commercially available computer systems were self-contained units, with terminals which were either integral with the processor or were installed adjacent to the main equipment [3]. In such systems the computing equipment and the terminals were interconnected by properly matched cables. Computer technology developed very rapidly, and it soon became common practice to distribute the terminals locally in different offices within a building and later, with the aid of the public switched telephone network (PSTN), nationally over wide geographical areas. The public switched telephone network was, however, designed for the transmission of analogue signals, with an overall channel bandwidth of about 3 KHz. In order to transmit digital signals over the telephone lines, digital data signals must normally be converted to analogue signals using devices called modems. The modems were developed to interface data terminals and digital equipment to the telephone network. Because of limitations set by noise and channel bandwidth, the maximum data rate obtainable over the public switched telephone network is about 2.4 kbits/s. To improve the digital transmission characteristics and obtain higher digital transmission rates, permanently connected private circuit leased lines became available, which permitted the incorporation of permanent correction for telephone line deficiencies [4]. Higher transmission rates of 4.8 kbits/s or even 9.6 kbits/s are available using private leased telephone lines. In most countries the public switched telephone network and the special leased telephone circuit are usually owned by the public telecommunication authorities (or PTT, standing for Post, Telephone and Telecommunication).

Some organizations normally hold large quantities of information at their central computer, such as the major clearing banks and airlines. The sub-branchs of these organizations are usually distributed throughout different geographical areas and are connected to the central computer through their terminals. In such organizations the sub-branchs require only occasional connection to the central computer facility and for such an application the switched telephone network provides the best method of connection. However, in many organizations it is not necessary to hold all the information centrally and hence it soon became common-place for organizations to have a number of autonomous computer systems located at different geographical areas. In such systems there was often a requirement for them to communicate with each other to exchange information [1].

To meet this type of interconnection, a more flexible communication facility was required. This meant that a different approach to data communication services had to be found as the communication link established using the switched telephone network and modems had a limited data capacity. Furthermore, in the telephone network the proportion of time during which information is actually being transmitted over the circuit is often quite small (ten of milliseconds) compared to the time required to set up a call through the telephone network (tens of seconds) [1]. This led to considerable inefficiency in the use of the telephone network when it was used for data transmission. More efficient use of the network can be obtained if the network circuits are used to interconnect network nodes and data is passed from one node to another in a store-and-forward mode of operation, which is the basis for packet-switching. The message data is divided up into suitable data packets, which enter the network through one of the nodes. They are then passed from node to node until they reach the destination node. A number of regional and national packet-switched networks have been provided for data transmission. Since, in the packet switching the interconnected computers are normally physically distributed over a wide geographical area, such a system is also referred to as a wide area computer communication network or WAN.

More recently, the continuing advances in integrated circuit technology and the growth of the digital speech network have resulted in many countries changing the mode of operation of the conventional analogue switched telephone network to an all-digital mode network. This means that, instead of requiring a modem to transmit data over telephone lines, it is possible to transmit data directly and at much higher rates than are currently used. Also, the call set-up times associated with this new generation of networks is significantly reduced. Because of their all digital mode of working and the ability of such networks to be used for both voice and data directly, they are referred to as integrated services digital networks or ISDNs [5].

With the advance of computer technology and the advent of the microprocessor and the associated advances in integrated circuit technology, it soon became common to find a multiplicity of different computer-based devices physically located within the same building, block of offices, university campus or a factory side. There is often a requirement for these systems to communicate with each other to exchange information. Since the computer-based devices are physically located close to one another there is, therefore, no need to make use of public network transmission facilities. The communication networks are therefore normally privately owned and designed to meet the special needs of the users concerned. Such a facility is generally designated a Local Area Network (LAN).

In the LAN, data transmission becomes simple due to the freedom to lay cables and design the network for one group of users and considerably higher transmission rates can be employed compared to the networks mentioned earlier. Local area networks are required by several types of users [4]. The most common of these is where it is necessary to link together a number of personal computers or to connect them to a remote host computer through a common channel in order to share resources, e.g., memory, data bases. The development of public electronic mail systems and other recent requirements such as the exchange of computer graphics information, is accelerating the application of LANs in the office and industrial environment. At the simplest level, a LAN may be an economical way to link a small number of computers (perhaps only one) to a number of remote terminals, printers or other digital devices [6-8].

2.1.1 Image Data Transmission Over Digital Communication Networks

Initially the communication networks users were concerned with the exchange of information such as text or numbers between computers and terminals over digital networks. However, nowadays there is increasing demand to exchange more extensive distributed information over digital networks. Because images convey extensive information much more efficiently than text or numbers, transmission of image data will play an important role in the future of telecommunications. Nowadays, transmission of image information over data communication networks such as facsimile services and videotex systems is widely used [2].

When dealing with transmission of image data over communication networks, the main problem one is faced with is the capacity of networks to enable the transmission of image data. In general, images contain a huge amount of information and require a very large bandwidth for transmission or storage. For example, for images based on pixel representation such as television pictures and video conference pictures a typical image with a spatial resolution of 512 x 512 pixels and with 8 bits/pixel intensity requires a transmission capacity of 512 x 512 x 8 = 2.097152 Mbits. This is a large number of bits to be transmitted in a communication network with a limited bandwidth or transmission rate. For example, using a telephone network with a transmission rate of 1200 bits/s, such an image would take almost half an hour to transmit. Since this time is so long, it is unlikely that such an image could reasonably be transmitted over communication networks with such a limited bandwidth. Thus it is highly desirable to reduce the amount of data necessary to represent images so that they can be transmitted or stored in an economical way.

To reduce the number of bits required to represent images, source coding techniques have been extensively used. The efficiency of the source image coding technique is measured by its compression ability, resulting distortion, and by its implementation complexity. There are three main image coding techniques for images based on pixel representation and containing a large amount of information such as television pictures or video conference images. These are, predictive coding, transform coding and hybrid (predictive / transform) coding [9-13]. Television broadcast coders and video conference coders operating at 34 Mbits/s and 1.5 Mbits/s are available. In communication networks with low transmission rate such as telephone networks, it is unlikely that adequate transmission rate will be possible to transmit such types of images. Thus, in order to save memory and network capability, more economical ways of representing image information have had to be developed. Facsimile pictures are also based on pixel representation. However, the intensity of any pixel is one of two states (black or white). Moreover, in facsimile services still pictures are transmitted, while in television or video conference pictures, multiple frames representing the movement in the picture are transmitted over a period of time. A smaller amount of data is therefore required to represent facsimile pictures.

One way of transmitting text and image information over conventional networks (telephone network) is using facsimile services. In facsimile services, many types of documents are likely to be transmitted, such as business letters, forms and diagrams, that can be satisfactory reproduced when quantized and transmitted in the form of two tones only, i.e., black and white. Group 3 facsimile standards are intended to enable the transmission of two-tone A4 size documents scanned at a (normal) resolution of 3.85 lines/mm and sampled at 1728 samples/line to be transmitted at 4800 bits/s in an average time of about 1 minute over the public switched telephone network. In facsimile, a source coding is used in which run lengths are encoded using a Modified-Huffman code [14-16]. At present, most facsimile traffic is carried by public telephone networks because of its availability. However, new digital facsimile equipment recently developed requires a high-speed transmission such as 9.6 kbits/s or 48 kbits/s, which is not available on public telephone networks. For this reason, facsimile communication systems based on packet switch data networks and ISDN networks have been developed [15, 17].

Another method of transmitting text and image data information over telephone networks is by using videotex systems. Videotex is a method of transmitting text and simple graphics over telephone lines. In these systems, the text and pictures obtained are accessed from service computers as pages and transmitted through telephone lines to the users and are reproduced using adapted television sets or low-cost graphics terminals. In videotex systems, three different source coding techniques are used to represent an image. These are, mosaic coding, photographic coding and geometric coding [18-20]. In mosaic coding, a page to be transmitted is treated as a fixed matrix of cells (matrix of 24 rows and 40 columns); each of these cells can display either 3 x 2 mosaic dots or one ASCII text character (American Standard Code for Information Interchange). The total number of code bytes required to produce a page is thus 960 bytes. Photographic coding is based on pixel representation of an image with transform coding usually used for source encoding. In the geometric coding, images to be displayed are described in terms of the drawing instructions of an image. These instructions correspond to certain geometric elements found in many drawings, namely, Points, Lines, Polygons, ... etc.

Due to the limitation of the conventional communication networks (telephone networks, packet switched networks WANs), facsimile services and videotex systems are usually used for transmission of image information. Digital networks such as ISDN networks can convey much higher transmission rates (64 kbits/s) compared to the conventional telephone networks. Such networks can therefore handle image data such as facsimile services and videotex systems in a much shorter time. The data transmission rates on local area networks (LANs) are high enough to satisfy most requirements and provide sufficient capacity to carry not only data, but voice and image information such as video conference pictures, or even television pictures [6].

2.1.2 Transmission Errors and Error Control Schemes in Digital Communication Networks

Efficient data transmission (text or image) is highly dependent on the characteristics of the transmission medium of the data communication networks. In many cases the transmission medium can take the form of a pair of wires such as in telephone networks, coaxial cables, or through the transmission of a light beam along a glass fibre. In each medium there are various impairments to the signal that can occur during the data transmission process. These are, principally, distortion as a function of distance, electrical noise and signal time delay. The effect of these impairments is to cause errors in data transmitted through the medium. Unfortunately, however well the communication system is designed, it is not possible to overcome the effects of channel impairments so that the received data is entirely error-free.

The effect of transmission errors depends to some extent on the type of transmitted data and may cause severe effects on the received data. Digital speech signals or image information such as television picture quality contain large amounts of redundant information and require comparatively large amounts of data for transmission. However, the occasional error in transmission will have little subjective effect on the received signal. Encoded data processing information, such as that for transfer of financial transactions, contains very little or no redundant information and usually requires less data for transmission. The integrity of the data transmission, however, is of the utmost importance, since an error in a single data bit could lead to a change of several orders of magnitude in the size of the sum concerned, with possible disastrous consequences [3].

To avoid the effect of transmission errors as far as possible, one practical solution is the use of error control techniques. Error control techniques have recently become an area of increasing importance in communication systems. In digital data communication systems there are two basic categories of error-control schemes used to protect the transmitted data. These are; automatic-repeat-request (ARQ) and forward-error-correction (FEC) [21-24]. In these schemes the transmitted data is encoded by proper channel error protection techniques and transmitted through the communication networks as sequences of codewords. In the basic ARQ system, an error-detecting code is used for detecting transmission errors. If no errors are detected in a received codeword, the received codeword is assumed to be error-free and is delivered to the user. At the same time, the receiver notifies the transmitter via a return channel and the next codeword will be transmitted. If the presence of errors is detected in a received codeword, the transmitter is requested, through the return link, to repeat the same codeword. Retransmissions continue until the codeword is successfully received. The ARQ scheme is widely used in data communication because it is simple and it provides high system reliability reasonably independent of the channel quality. However, it has the disadvantage that as the channel error-rate increases the time delay of suppling data information to the user is increased.

In an FEC scheme, an error-correcting code is used for correcting transmission errors. When the receiver detects the presence of errors in a received codeword, it attempts to correct the errors. If the receiver fails to correct the errors, the received data block will be incorrectly decoded and erroneous data will be delivered to the user. Since no retransmission is required in an FEC system, no feedback channel is needed and the throughput efficiency of the system is maintained at a constant level (equal to the code rate) regardless of the channel error rate. However, FEC systems have some drawbacks. Firstly, it is hard to achieve high system reliability as the channel error-rates increase. Secondly, in order to obtain high reliability, a powerful error correcting code must be used to correct error patterns. This makes decoding hard to implement and expensive. Another disadvantage of error correction codes is the large amount of redundancy usually required for these codes.

The choice between forward error correcting and ARQ techniques depends on the availability of a return channel, the economics of implementing the coding and decoding systems, the transmission time requirements and the probability and acceptability of transmission errors in the received data.

2.2 Requirement for Transmission of Image Data Over Digital Networks Involving Mobile Terminals

The transmission media so far discussed have all used physical media such as telephone lines to carry the transmitted data information. An extension of the telephone facility to mobile terminals has taken place recently with the introduction of cellular mobile radio telephony. Mobile radio communication systems, which are mainly designed for voice communications, have seen great success in many countries. As the communication to and from mobiles becomes popular, the demand for other services, such as transmission of data or image information is rapidly increasing [25-30]. The reason why image data transmission to mobile terminals will increase is that a large amount of data in the form of graphic images is being held in data bases organized by mainframe computers. This is particularly the case with public services such as the Police, Fire service, Gas and Electricity and other services, which make extensive use of computers at their headquarters. To be able to access this information directly from mobile terminals is of major importance to these services. With the recent advances and wide-spread use of computer graphics, the plans of all large buildings, floor plans, campus maps, network diagrams could now easily be stored in computer files, ready for immediate transmission to the mobile users in an emergency. This information can be as detailed as required, can be updated easily and can be available quickly for transmission over mobile channels. This sort of service is already used over digital networks such as local area networks. However, they cannot be applied directly to mobile terminals. This is because lower transmission rates and higher error rates are obtained over mobile channels in comparison to normal digital networks. The aim of this project is study the requirements to transmit graphics image data over digital networks involving mobile terminals [31].

2.2.1 Limitation of Mobile Channels

It has been shown that transmission of image information provided by videotex and facsimile services is already used over fixed digital networks. Transmission of high definition pictures such as television picture quality can only be met over high rate digital networks such as LANs. However, these services cannot be applied directly to the mobile terminals. This is because mobile channels differ from fixed communication channels in that the signal received is variable in strength and frequently falls below the acceptable threshold level at the receiver. Fixed network channels suffer from various types of noise which lead to transmission errors. Their characteristics, however, are readily predictable and are stable over long time periods. In mobile channels, the signal quality is much lower than that in telephone lines. Moreover, the received signal suffers from multipath fading phenomena [32-38]. It is generally accepted that the mobile channel is a poor communication channel. The majority of errors on mobile digital radio channels occur in bursts rather than as random errors which are more typical on the conventional digital networks. It is expected that if a communication system works well over this channel it should perform equally as well, or with better performance, over digital communication channels. Thus rates of digital transmission over mobile radio channels will be low compared to those available over conventional digital networks, and error-rates are significantly worse.

2.2.2 Data Transmission Over Mobile Channels

Mobile radio communication systems designed for analogue voice communication have been very successful [25]. There is now growing interest in extending the mobile channel to incorporate new mobile transmission techniques similar to those used for the transmission of digital data over the present fixed systems. Several systems have been proposed for data transmission in mobile channels [39-46]. The major drawbacks facing the transmission of data over mobile channels is the transmission errors. The effect of mobile transmission errors on voice transmission is minor because of the inherent redundancy in speech. In fact, a mobile radio system may give a very high performance when used purely for voice transmission. However, the effect of the transmission error characteristics of the mobile channel on data is more severe. This is because in general there is little or no redundancy in most data transmission applications. The result therefore is data error. To transmit data over a mobile channel, powerful channel error protection techniques must be used to protect the integrity of the data.

In the U.K., the Total Access Communication System (TACS) cellular mobile radio network commenced public service in 1985 [47]. The requirements for data transmission over the TACS network have been described [28, 41, 48]. In TACS, data is divided into message blocks. Forward error correction and automatic repeat request are used to overcome errors due to the mobile fading channel. Interleaving techniques are used to randomize error bursts. Other systems, such as the AMPS (Advanced Mobile Phone Services), are also based on transmitting the data in message blocks and providing an adequate channel error-control technique to overcome the transmission errors [49].

The extraordinary success of cellular mobile radio systems so far in its analogue form and the increasing demand for digital data transmission over mobile channels augurs well for the introduction of digital mobile cellular radio. For example, it is planned that a common cellular mobile network known as pan-European cellular mobile network will be in operation for all the European countries in 1991-1992. In the planned pan-European mobile network speech transmission still remains the essential service offered. However, there will be other types of services, e.g., data transmission such as transmission of short messages, access to mail box, teletex. Services involving transmission of image data over the network, such as transmission of facsimile images and transmission of image data based on videotex services, are also offered [26, 28-30].

2.2.3 Transmission of Low Bit-Rate Image Data Over Mobile Channels

A major drawback to the transmission of image data over mobile channels is the limitation of the mobile channel to handle the large amount of data in images. Moreover, the effect of mobile channel errors is also another major drawback. It is unlikely therefore that adequate transmission rates will be possible to transmit pictorial information of a television quality or video conference pictures represented on a full pixel basis. Image information that requires comparatively low bit-rates have been employed for transmission over mobile radio channels. In general, low bit-rate images are those reproduced by videotex systems or by two tone facsimile services.

Transmission of image data represented by the videotex system (Prestel) over mobile channels has been proposed [50]. Prestel is the trade name of the videotex system (viewdata) used in Great Britain. In this system, data information such as text or simple graphics are accessed from a central computer as pages and mosaic shapes are used to represent the graphics. Each mosaic shape is represented by one ASCII character. It was shown that transmission errors affect the received image data and, to reduce the effect of errors, an error correction code was proposed. In the Prestel viewdata, the number of code bytes used to access a graphic image from the central computer is fixed (960 bytes), irrespective of the graphic details. Moreover, the resolution of images represented by Prestel is fixed and is considered to be coarse for normal graphics.

Recently, several systems have been proposed for transmission of facsimile digital data over mobile channels [51-53]. One author [51] has proposed a powerful channel error protection scheme to protect the encoded Modified-Huffman facsimile data. An error correction code with an automatic repeat request scheme was employed to reduce and avoid transmission errors. An interleaving technique was used to randomize the burst error caused by the mobile channel. To provide more reliable transmission of the Modified-Huffman encoded facsimile data, a robust channel error protection was proposed [52]. Diversity techniques and forward error protection were used for channel protection. An interleaving technique was used to randomize the burst errors caused by mobile channels and a minimum transmission time of one minute was required for an A4 document. The method of assessing the performance of the received facsimile image data was estimated by subjective tests [51, 52]. The problem of transmitting low resolution raster scanned documents to mobiles was considered by Wyrwas and Farrell [53]. About 30 seconds was required to transmit a low resolution document. An interleaving technique was also used to randomize the burst errors caused by mobile channels. In facsimile systems, an A4 transmitted document is scanned at a (normal) resolution of 3.85 lines/mm and 1728 sample/line, and then encoded, usually by the Modified-Huffman code. This is done irrespective of the content of the document, which might be a simple image. Therefore there is usually a minimum transmission time of about 1 minute per document.

The system which will be described in this thesis attempts to provide a source coding in which the amount of data required to represent an image is proportional only to the image details. Line diagram images such as street maps, floor plans, campus maps, networks diagrams are considered to be of interest to various mobile users and are considered for transmission in this thesis. Some shapes of line diagram images could be simple, for example, floor plans, and it is highly desirable to represent such simple images with as small amount of data as possible so that very short transmission times and small storage sizes would be achieved. To satisfy this requirement, a low bit-rate source coding technique known as character encoding, based on geometric codes, is presented. Character encoding has recently been developed and standardized by the International Standards Organization (ISO) and is proposed to represent or store graphics image data in compact format in computer graphics metafiles (CGMs) [54-57]. Character coding uses drawing instructions to represent graphics images. The instructions correspond to certain geometric elements found in many graphics such as Lines, Markers, Polygon, Rectangle, and Text. The amount of data required to represent or store a line diagram image will therefore depend on the number of drawing instructions contained in the image. An image with few details would therefore require a small amount of data for storage and a short transmission time.

2.3 Representation of the Mobile Radio Channels

It is well-known that the signal strength received at the antenna of a moving vehicle in a mobile channel varies randomly with a Rayleigh distribution. When the signal falls below the acceptable threshold level at the receiver, a fade occurs that causes any digital data transmitted over the mobile channel to be corrupted with a noise burst. The length of these bursts depends on the duration of the fade, which is in turn a function of the fade level, the vehicle speed, and other mobile channel parameters [32-38].

To obtain the effect of mobile transmission errors on the transmitted image data, source errors representing the characteristics of mobile channels at various environments are required. The source errors are usually recorded or stored in computer files ready for use to assess the performance of the received image data.

A common method used to obtain mobile source errors is based on field measurements, where a continuous data signal is transmitted from a base station to a vehicle moving over certain routes. Digital recording of the signal level and error patterns are made for different mobile environments and are used for analysing the performance of the digital data transmission [58-61].

In situations where the field strength measurement is not easily available, then the source errors can be represented by channel modelling. Although modelling the mobile channel suffers from certain shortcomings compared to field measurements, they can be used successfully to estimate fading behaviour. The channel models are best used on a relative basis, to compare different error correction techniques, for example, rather than as absolute measures of performance [62, 63]. The two-state Markovian model known as the Gilbert-Elliott model [64, 65] has been used for modelling bursty channels such as mobile channels [66, 67]. The two-state model is composed of a good (non-fade) state and a bad state or burst state (fade). A sequence of binary noise digits is generated digit by digit by the Markovain chain representing the fade and the non-fade states and is stored in a computer file.

In some mobile communication systems it is required to obtain the probability of one error or more within a certain length of the transmitted packet, which is known as the packet error rate. In such systems, a mathematical model based on the Rayleigh distribution is used to represent the mobile channel. In this model, a data system is assumed to have a sensitivity threshold, where the communication is assumed to be successful for signals above threshold. Likewise, at signals below threshold, it is assumed to be unsuccessful [68-70, 137].

2.4 Performance Analysis of the Received Image Data Subjected to Mobile Transmission Errors

The performance analysis of the received image data subjected to mobile transmission errors with and without channel error protection techniques is one of the major concerns of this thesis. The methods adopted of assessing the performance of the received image data are basically subjective assessment tests [71-74]. The subjective assessment has its basis in the visual observation of the reproduced image, for which computer plots of reconstructed images are used for comparison between the original image and its reproduced image, including the effect of transmission errors in various mobile environments. In this thesis, line diagram images consisting of several drawing instructions are used for transmission. Certain errors within an image might be not perceptible from the quality point of view, but could nevertheless be misleading from the usefulness point. Two types of subjective tests are therefore carried out. The first relates to the quality and the second relates to the usefulness of the image. The CCIR recommendation 500 used for the subjective assessment tests of the quality of the television pictures can also be used for subjective assessment of other types of pictures [51, 52, 75, 76]. The subjective assessment tests of the quality of the line diagram images in this work are therefore conducted based on the CCIR Rec. 500.

CHAPTER 3

LOW BIT-RATE IMAGE DATA IN COMMUNICATION SYSTEMS

3.1 Introduction

When dealing with transmission of image data over communication networks, the main problem one is faced with is the capacity of networks to enable the transmission of image data. The effect of transmission errors is another limitation. The communication channel path involved in this work includes a conventional digital network, such as a local area network provided within an office complex, or university campus, or ISDN in conjunction with a mobile radio terminal. The communication channel can also be via the public switched telephone network (PSTN) in conjunction with a mobile radio terminal. The mobile radio networks are characterized as having restricted bandwidth leading to low rates of transmission. Moreover, the mobile radio channel is worse than the conventional digital networks or the PSTN in terms of transmission errors. It is expected, therefore, that the more serious effect on the transmitted image data will be caused by the mobile channel. It is unlikely, therefore, that adequate transmission rates in mobile networks will be available to transmit moving images consisting of large amounts of data, such as television or video conference pictures represented on a full pixel basis and where the intensity of each pixel is encoded by several bits. To enable the transmission of image data over a restricted transmission channel, low bit-rate images using smaller amounts of data, such as facsimile images and videotex images, have been implemented. These images are basically stationary images and can be stored in computer files, or transmitted through conventional communication networks such as telephone lines, using much lower capacity.

In this chapter, methods of transmitting facsimile and videotex stationary image information over public switched telephone networks are examined. Proposed systems for extending the transmission over mobile terminals are also given. Finally, a proposed source encoding scheme, which is used later in this thesis for representing basic line diagram graphic images for transmission over digital networks involving mobile terminals, is presented.

3.2 Facsimile Systems

In telecommunications, facsimile is defined as a service to read and encode documents and pictures, transmit them over telephone-type circuits and reconstitute them at the distante terminal. The transmission circuits may include high speed digital networks, microwave and satellite links. The transmitted document can be newspapers, letters, weather maps, or other types of document which may contain hand written information. In order to transmit a facsimile document, a communication link has to be set up between the transmitter and receiving terminal. The document whose contents are to be transmitted is then encoded line by line, scanning each line from left to right from the top-left position of the document [16].

CCITT (International Telegraph and Telephone Consultative Committee) have defined two recommendations (T.2 and T.3) for the transmission of documents by facsimile over the general public switched telephone network (PSTN) [14]. These refer to Groups 1 and 2 type facsimile apparatus and allow A4 size documents scanned at 3.85 lines/mm to be transmitted in 6 and 3 minutes respectively, using analogue techniques. Faster transmission cannot readily be obtained using analogue techniques because of the restricted bandwidth of telephone circuits. However, the transmitted documents can be satisfactorily reproduced when quantized and transmitted in the form of two tones, i.e., black and white. The CCITT facsimile study group have therefore defined recommendation (T4) for Group 3 type apparatus, where documents are digitally transmitted in the form of two tones, i.e., black and white. In the standard, a two-tone A4 document scanned at a normal resolution of 3.85 lines/mm and sampled at 1728 samples/line is transmitted at 4800 bits/s in an average time of about a minute over a PSTN circuit using source coding to reduce redundancy.

The CCITT have also adopted an international standard for the Group 4 facsimile apparatus [15]. The G4 facsimile is designed to have a wide range of application from the basic facsimile transmission to a sophisticated teletex-facsimile mixed mode of operation. Group 4 facsimile is designed to be used mainly on public data networks (PDN) including circuit-switched, packet switched, and the integrated services digital network (ISDN). The apparatus may also be used on the public switched telephone network (PSTN).

In digital facsimile, redundancy reduction is achieved by coding the lengths of black and white runs using a technique known as run-length coding. When the coding is applied in one direction (usually the horizontal scan) it is known as one-dimensional (1-D). When the coding is applied in both the spatial directions it is known as two-dimensional (2-D) coding. Huffman coding is a near optimum method for one-dimensional coding. However, a pure Huffman code has the disadvantage of requiring a large code table, most of which is allocated for storing codes that are rarely used. This implies a high implementation complexity which can be reduced considerably by providing individual Huffman code words only for the frequently occurring short runs and coding longer runs in a different way. For this purpose the CCITT recommended the modified Huffman coding which assigns individual Huffman code words to run lengths up to 63 pels. Run lengths greater than 63 pels are broken into 2 run lengths, namely a make-up run length having a value N x 64 (where N is an integer between 1 and 27 so that N x 64 is equal to, or shorter than, the value of the run length to be transmitted) and a terminating run length having a value between 0 and 63. The terminating run length specifies the difference between the make-up run length and the actual value of the run to be transmitted. This reduces the number of code words required and simplifies implementation. Based on these criteria, a one dimensional run-length coding scheme using a modified Huffman code was chosen as a basic Group 3 standard [14, 77, 78].

The CCITT have also proposed a two-dimensional code called the modified READ code (Relative Element Address Designate) as an option in the T-4 Recommendations for Group 3 equipment. The modified READ codes the position of a transition element (i.e., the first black pel after a white run or vice versa) with respect to a corresponding transition element on the reference line (which lies immediately above the current line) or with respect to the previous transition on the current line. After a line has been coded, it becomes the reference line for the next coding line. In order to prevent possible propagation of errors in the vertical direction, every Kth line is coded one-dimensionally, where K is set to 2 at normal resolution and set equal to 4 at high resolution.

For the digital transmission of facsimile documents on telephone lines, one and two-dimensional source encoding algorithms have been implemented. For a resolution of 3.85 lines/mm there is no great difference between the transmission times of a one-dimensional and two-dimensional code. In the case of a higher resolution of 7.7 lines/mm the two-dimensional codes provide a considerably shorter transmission time than the one-dimensional codes. The two-dimensional code is potentially more susceptible to errors than the one-dimensional code. It is generally said that a bit error probability of less than 10^{-4} is required for Group 3 facsimile to transmit an image signal with good quality [79]. In general, the Group 3 apparatus requires an average time of 1 minute for an A4 document to be transmitted over a public switched telephone network. ARQ and FEC error control techniques were considered but not incorporated in the Group 3 standard because they are complex and add extra cost to the facsimile receiver equipment.

Recently, transmission of digital facsimile services using the Group 3 apparatus over mobile channels has been proposed using analogue voice systems over a mobile channel [51]. A voice band modem was selected in which a transmission rate of 4800 bits/s was achieved using multilevel modulation, 8-phase PSK. Heavy channel data protection, consisting of FEC together with selective repeat ARQ, was employed to achieve good image quality under fading. In order to get better FEC performance, an interleaving technique was adopted to randomize burst errors. The performance of the received images was evaluated using the 5-point score subjective tests. It has been reported that the performance of the subjective tests was acceptable at an average bit error rate (BER) up to of 0.01. With higher BER values the performance was seen to degrade.

A further development of Group 3 facsimile over digital mobile radio uses the modified Huffman facsimile data encoded with a random error correcting code [52]. In this case, bit interleaving was employed to randomize the burst errors produced by the multipath fading channel. Two branch time diversity was implemented to achieve robust data transmission over the fading radio channel. A channel transmission rate of 16 k bits/s was chosen. The received picture quality was subjectively evaluated. It has been reported that an average subjective score of 3 to 4 of the 5-point score can be achieved at an average bit error probability of 5 x 10^{-3} to 10^{-4}. Under such conditions a transmission time of 1 minute was required for an A4 document.

Wyrwas and Farrell [53] have investigated the problem of transmitting low resolution documents (255 samples/line and 196 lines) to mobiles. An interleaving technique was used to randomize burst errors caused by mobile channels. Under 30 seconds was required to transmit a document with a channel bit error rate of up to 1 in 50.

3.3 Videotex Systems

Videotex is the generic name used internationally to refer to public-accessed information systems that use either a modified television set or personal computer to display computer-based data information such as text or images in the home and office. The data information obtained is accessed from service computers as pages and are intended to be displayed using adapted television sets. The data to be displayed is received either from a data connection over a telephone line or encoded in the unused flyback scan lines of an over-the-air television or cable television signal. Systems using telephone networks to access the service computer are called telephone based or interactive videotex (two-way) systems as shown in Fig. 3.1.

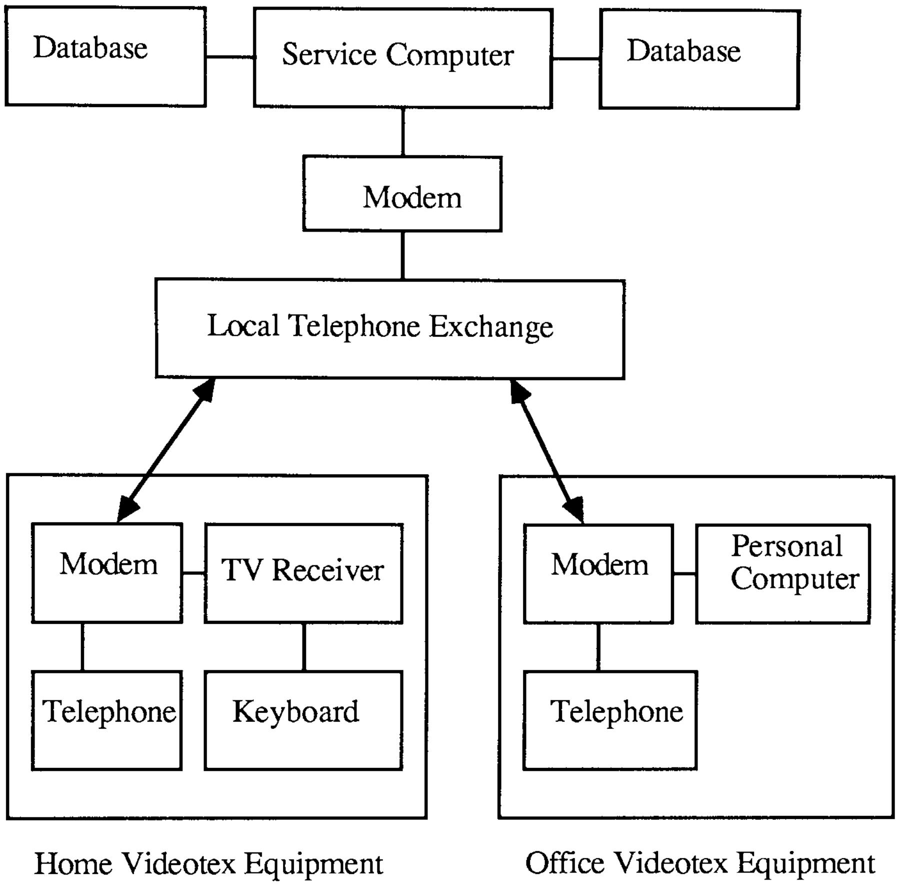


Fig. 3.1 Typical videotex configuration (data is transmitted at 1200 bits/s to terminals, 75 bits/s from terminals)

In operation, a subscriber to videotex is able to select from a number of pages of material which he may wish to display and view. Information suppliers provide a central data bank of information covering a wide range of topics. The user's commands are forwarded to the service computer. There the desired information is retrieved and sent back to the terminal. Prestel is the trade name of the interactive videotex system used in the U.K. introduced in 1975 by the British Post Office (now British Telecom.). Nationwide public service of Prestel began in 1979. This was the world's first public videotex service, which was followed by other videotex systems in a number of other European countries based mostly on Prestel technology. The videotex systems in the European countries are unified as one European standard CEPT (Conference of European Posts and Telecommunication administration). In North America, Canada's Telidon - a system based on PDI (Picture Description Instruction) - appeared in 1981, and this is now unified as NAPLPS (North American Presentation Level Protocol Syntax). In Japan, on the other hand, CAPTAIN (Character and Pattern Access Information Network) - a videotex service based on a different data syntax from either CEPT or NAPLPS - has been operating since 1984.

There are therefore three videotex syntaxes in the world today - CEPT, NAPLPS and CAPTAIN - and videotex services in different countries are based on one of these three [18, 19, 20, 80, 81].

Broadcast videotex (teletext) is a service system based on the use of a one-way communications channel such as over-the-air television. In teletext, data information is continuously transmitted and the user's terminal selects and waits for the desired pages. The idea of teletext can be traced back to work in the U.K. in the early 1970's. Ceefax and Oracle, two teletext systems operated by the BBC (British Broadcasting Corporation) and the IBA (Independent Broadcasting Authority) respectively, have been operational since 1978 [82, 83].

3.3.1 Image Coding in Videotex Systems

Videotex employs methods of transmission fundamentally different from ordinary television. Transmission is digital. Pages to be displayed are generally stored in computer files and transmission rates can be quite small. There are three coding options in use for representing image information in videotex systems [18, 20, 84];

- Mosaic Coding
- Photographic Coding
- Geometric Coding

Mosaic Coding

This method is the basic means of transmitting text information to the videotext terminal with extensions to handle graphic shapes by using mosaic graphics characters. Mosaic coding has been implemented in the videotex systems being used in Great Britian (Prestel) and Europe [19, 80]. Three modes of mosaic coding can be distinguished, alphanumeric, graphic, and DRCS (Dynamically Redefinable Character Sets). The display area in all modes is divided into a fixed matrix of cells, typically a matrix of 24 rows and 40 columns, each cell being a matrix of pixels. A cell can display a mosaic character; the shapes of these characters are different in the three options. All character shapes displayable by a receiving terminal are stored in the terminal memory as binary dot matrices. Each displayable character is accessed by one byte of information, one ASCII character (American Standard Code for Information Interchange), from the computer service through a telephone line. Thus a full screen of characters (960 characters) requires 960 bytes of information.

The displayed alphanumeric alphabets are based on ISO standard 646 (International Standards Organization), equivalent to BS 4730 (British Standards) [85], and its extensions to special symbols and national alphabets, ISO 2022 equivalent to BS 6856 [86]. Graphics alphabets are used to create simple pictures and diagrams. Graphics are produced by dividing each character position into six elements (3 rows by 2 columns), which gives 64 different shapes for each position. The effective resolution over the entire screen for this approach is 3x24 =72 by 2x40=80 positions. This resolution is fixed and is expected to be coarse for normal images. At such resolution the shapes of the reproduced images appear square-edged. DRCS encoding is used to display additional characters which are not stored in the terminal's memory. The shapes of the new characters are transmitted.

Transmission of image data represented by the videotex system Prestel over mobile channels has been proposed [50]. It was shown that mobile transmission errors affect the received image data. To reduce the effect of errors, a (15, 7, 2) error correcting code was proposed for protecting the encoded information data consisting of seven bit ASCII codes.

Photographic Coding

This method is used in cases where the mosaic coding and the geometric coding, described below, would fail to represent the image in sufficient detail. The photographic coding is very similar to digital television. Since the transmission speed of image data over the telephone line is lower than that required for direct image display at the normal scan rate, the picture must first be stored in a memory before scanning. Thus, only still images are transmitted by this method. An image to be transmitted is scanned on a pixel basis, digitized, the data compressed using a suitable source coding and then stored. Transform coding such as, Fourier, Hadamard, or other transformation, is usually adopted as source coding. The data is then transmitted to the terminal, where it is decoded and written into a frame buffer and displayed. The main problem with photographic coding is conveying the enormous amount of information that is contained in a still television frame. For example, an image with 300 pixels per line, 500 lines gives 150000 pixels. For the luminance signal, 1 byte per pixel is required to encode the intensity and thus a total of 1.2 Mbits is required for transmission [18]. This is a large amount of data to be stored in the data base and in the terminal. Moreover, the transmission capacity of conventional public telephone lines is much too low to handle such image data since it would require an excessively long transmission time. Nevertheless, using a suitable source coding considerably reduces the amount of the transmitted data required.

Geometric Coding

In this method, images to be displayed are described in terms of the drawing instructions of which they composed. These instructions correspond to certain geometric elements found in many drawings such as Lines, Markers, Polygon and Rectangle. Thus a straight line is specified by a plot line command and the coordinates of its end points. Similarly, a rectangle is specified by a plot rectangle command and the coordinates of two opposite corners of the desired rectangle. This is a much more natural and concise way of describing a diagram than scanning it or converting it into mosaics. This approach has its roots in many graphical languages used in computer graphics systems and was adapted to the needs and possibilities of videotex. Geometric coding can describe complex images more efficiently (higher resolution) than can mosaic. The coordinate system for the description of a geometric drawing is based on a cartesian number system ranging from 0 to 1 over the visible area of the display screen. This is independent of the physical resolution of the apparatus, which may be a television set with an order of 256 positions of resolution in the horizontal direction or a high resolution display apparatus of 1024 positions (pixels), or any other resolution. Since coordinate positions are specified as a fraction of the width of the display screen, the least significant bits may be dropped when they are not needed, such as in low resolution terminals. Thus low to high terminal resolutions can be used, which is an important advantage of geometric coding. For an image resolution of 512 x 512 pixels, 3 bytes are required for the X, Y coordinate information, where each byte may be organized with 3 bits of X and 3 bits of Y data.

Geometric coding is different from mosaic or photographic coding. In the later two cases there is a relation between bytes of code and picture area that is direct and independent of picture content. The amount of code bytes required for geometric coding is related only to image complexity. For example, a simple map would require fewer bytes than would a map containing more detail. This is an important feature, as simple graphic images would require small storage sizes and short transmission times. The Open

University in the U.K. has developed a low-cost audio-visual teaching system known as Cyclops based on a videotex system and using a geometric code [87, 88]. The Cyclops display terminal decodes data (text and geometric drawing instructions) received from a computer or a telephone line or a cassette tape. It produces a video signal suitable for driving a conventional television receiver. In North America, Canada's Telidon, which is now unified as NAPLPS is based on geometric coding [89-92].

The approach of geometric encoding has its root in many computer graphic systems such as GINO-F in the U.K. and similar systems in other countries. As changes in graphics devices occur, these packages are gradually becoming obsolete. Therefore, there has been a need to define an international graphics standard and the result is the Graphical Kernel Standard (GKS) system published by the International Standards Organization (ISO 7942, equivalent to BSI 6390) [93]. The GKS system was also proposed for a videotex system of geometric display [94]. GKS provides basic drawing actions through two types of routine, output primitive routines, which perform the drawing, and the attribute setting routines, which control the appearance of the drawing. GKS provides six output primitives;

POLYLINE; Draws a sequence of connected straight lines between points.
POLYMARKER; Draws a given marker at each of a sequence of points.
TEXT; Produces a string of characters based on ISO 646 aligned to a given position.
FILL AREA; Draws a polygonal area defined by a sequence of points which may be hollow or filled in a specified manner.
CELL ARRAY; Maps a rectangular array of cells of varying intensity or colour onto the output device.
GENERALIZED DRAWING PRIMITIVE; Provides access to other drawing facilities available on a device that cannot be described in terms of any of the above primitives, such as the drawing of circular or elliptic arcs.

Each output primitive has its own attribute routines which control the geometric or the non-geometric shape of the primitive. The GKS system operates on the Aston University main frame computer and is used for generating graphics images.

3.4 Proposed Low Bit-Rate Source Encoding for Line Diagram Graphic Images

In this thesis, a source encoding is selected in which the amount of data required to represent an image is proportional to the image details. Line diagram images such as street maps, floor plans, campus maps, networks diagrams are considered to be of interest to various mobile users and are considered for transmission in this thesis. Some shapes of line diagram images could be simple, for example, floor plans, and it is highly desirable to represent such simple images with as small amount of data as possible so that very short transmission times and small storage sizes would be achieved. This feature, as mentioned earlier, is important for low rate mobile channels. To satisfy this requirement, a low bit-rate source encoding technique based on geometric codes known as character encoding, is presented. Character encoding, using drawing instructions, has recently been developed and standardized by the International Standards Organization (ISO) and is proposed to represent or store image data in compact format in computer graphics metafile (CGM), [54-57].

3.4.1 The Computer Graphics Metafile (CGM)

The Computer Graphics Metafile (CGM) provides a file format suitable for the description, storage and communication of graphical information in a device-independent manner. The file format consists of an ordered set of elements which describe images in terms of commands (opcodes) to draw basic geometrical instructions such as Line, Marker, Polygon, Rectangle, etc., at specific positions in the overall image. Text characters based on the ISO 646 equivalent to the BS 4730 can also be incorporated into CGMs in a regular way. The structure of the metafile is as follows;

BEGIN METAFILE	METAFILE DESCRIPTOR	< PICTURE >	END METAFILE

The BEGIN METAFILE element is followed by the METAFILE DESCRIPTOR. After this the pictures follow, each independent of each other. Finally the metafile is closed with an END METAFILE element. The structure of a picture within a metafile is as follows:

BEGIN PICTURE	PICTURE DESCRIPTOR	BEGIN PICTURE BODY	< ELEMENTS >	END PICTURE

A picture consists of a BEGIN PICTURE element, a PICTURE DESCRIPTOR element, a BEGIN PICTURE BODY element, and an arbitrary number of graphical primitive (geometric drawing) and attribute elements which describe the picture and, finally, an END PICTURE element. The graphical primitive elements are those elements that describe the visual components of a picture. In the CGM, the term graphical primitive element is used which is identical to the term geometric drawing element mentioned previously.

Five types of graphical primitive elements are defined for the CGM: line elements, marker elements, text elements, filled-area elements and cell array element. For a certain graphical primitive element there are several categories [56]. For example, the line elements composed of two general line elements, POLYLINE and DISJOINT POLYLINE, and three line elements relating to circles and ellipses. In this work, certain types of graphical primitive elements are selected to describe or store graphic images, as will be shown later. The picture elements consist of an ordered set of graphical elements used to describe pictures in a completely device-independent way. Each graphical element is composed of one opcode followed by a number of parameter data.

The amount of data required to represent or store a graphic image will therefore depend on the number of graphical elements contained in the image. An image with few details would therefore require a small amount of data for storage and a short transmission time. The CGMs store images in a resolution independent manner. These images can be redisplayed on a low-resolution display terminal and still be displayed on high-resolution display terminals or printed on high-resolution printers.

There are three standard methods of encoding the metafile elements. These are Binary encoding, Clear-Text encoding and Character encoding. The Binary encoding of the CGM provides a representation of the metafile elements that can be optimized for speed of generation and interpretation but is not well suited for exchange between computers and terminals of different arithmetic data types. The encoding uses binary data formats that are much more like the data representation used within computer systems than the data formats of the other encodings. The elements of a metafile are represented as a variable length data structure, each consisting of opcode information (element class, element identification, and the length of its parameter data) and, finally, the parameter data of the X, Y coordinates. For measuring the length of elements the metafile is partitioned into octets, which are 8-bit fields. The structure is also partitioned into 16-bit fields called words [96]. The Clear-text encoding provides maximum readability for ease of use by humans but, generally, pays a heavy penalty in the amount of data storage required [97]. The Character encoding of the CGM provides a representation of the metafile elements intended for the situation in which it is important to minimize the size of the metafile. The encoding provides a highly compact metafile, suitable for systems with restricted storage capacity or transmission bandwidth [57]. The character encoding has been developed in collaboration with the ISO subcommittee responsible for coding of videotex graphic systems. Because of the restricted bandwidth of the mobile communication channel, and in order to store or represent line diagram images in a minimum storage size, we have selected the character encoding as a source encoding for representing line diagram images.

3.4.2 The Character Encoding for Representing and Storing Graphic Images in Computer Graphics Metafiles

In the character encoding, each CGM graphical element is composed of one opcode followed by a number of parameter data as required. A 7-bit code or 8-bit code table chart can be used to describe the CGM graphical elements [54, 56-57]. In a 7-bit environment, the code table is presented as a table of eight columns and sixteen rows. A character, or bit combination, has seven bits, numbered b1 to b7, from least significant to most significant. Bits b7, b6, and b5 address the columns, and bits b4, b3, b2, and b1 address the row. A " col/row " notation is used in which " col " is the column number, and " row " is the row number. For example, " 1/11 " refers to the bit combination in column 1, row 11 of the code chart which corresponds to binary 0011011. In an 8-bit environment, the code table has sixteen columns and sixteen rows. Bits b8, b7, b6, and, b5 address the columns, and bits b4, b3, b2, and b1 address the rows.

In this work the 7-bit code table has been adopted to describe the CGM elements as shown in Table 3.1. The 128 bit combinations of the 7-bit code represent control characters (C0) and graphic characters (G-sets). The C0 sets occupy columns 0 and 1 of a 7-bit code table. In general, the C0 sets are used to control the shape and type of the G-sets. The G-sets are coded character sets of 94 or 96 characters designated to represent graphics and text information in the CGM [57].

The Table chart for the G-set graphic information is subdivided into two fields, one for opcodes and the other for the parameter data. The opcodes are encoded as a sequence of bit combinations from columns 2 and 3 of a 7-bit code chart. The basic opcode set consists of single-byte and double-byte opcodes.

Table 3.1 The 7-bit code table used for describing computer graphics metafile elements

				b7 b6 b5	0 0 0	0 0 1	0 1 0	0 1 1	1 0 0	1 0 1	1 1 0	1 1 1
b4	b3	b2	b1	Col Row	0	1	2	3	4	5	6	7
0	0	0	0	0	THE C0 SET			A G-SET OF 94 OR 96 BIT COMBINATIONS				
0	0	0	1	1								
0	0	1	0	2								
0	0	1	1	3								
0	1	0	0	4								
0	1	0	1	5								
0	1	1	0	6								
0	1	1	1	7								
1	0	0	0	8								
1	0	0	1	9								
1	0	1	0	10								
1	0	1	1	11								
1	1	0	0	12								
1	1	0	1	13								
1	1	1	0	14								
1	1	1	1	15								

Single-byte opcodes are coded from column 2 of the code chart. Bits b4 to b1 are used to encode the opcode. Bit 7 = 0 is the opcode flag bit and bit b8 is the parity bit or omitted bit in the 7-bit code table. For example, when b1=0, b2=0, b3=0, and b4=0, then the opcode means POLYLINE. In double-byte opcodes the first byte is from column 3 and the second byte is from column 2 or 3 of the code chart. Single-byte opcodes are used to encode the main graphical elements such as POLYLINE, POLYMARKER, TEXT ...etc. Double-byte opcodes are used to encode the remaining drawing instructions and various attributes related to the drawing instructions such as line type (e.g., solid, dash, ...etc.), marker type (e.g., dot, plus, ...etc.). Table 3.2 shows the opcodes used with the single-byte opcodes.

Table 3.2 Single-byte opcodes used in character encoding

Opcode	7-Bit Coding	Binary Symbol
POLYLINE opcode	2/0	0100000
DISJOINT POLYLINE opcode	2/1	0100001
POLYMARKER opcode	2/2	0100010
TEXT opcode	2/3	0100011
RESTRICTED TEXT opcode	2/4	0100100
APPEND TEXT opcode	2/5	0100101
POLYGON opcode	2/6	0100110
POLYGON SET opcode	2/7	0100111
CELL ARRAY opcode	2/8	0101000
GENERALIZED DRAWING PRIMITIVE opcode	2/9	0101001
RECTANGLE opcode	2/10	0101010

The parameter part of a CGM element may contain one or more parameters, each consisting of one or more bytes. The parameter data is used to encode X, Y coordinates of points that represent a line, a position of a text to be displayed or a position of a marker to be indicated. The required resolution of the X, Y coordinates of a point depends on the number of the parameter data bytes used. All parameters are coded in columns 4 through 7 of the 7-bit code chart. However, the coded representation of a text parameter may include bit combinations from other columns of the code table. Columns 0 and 1 are used only for control codes.

Parameter data is encoded using basic format or bitstream format. In basic format, each parameter is encoded as a sequence of one or more bytes; bit 6 of each byte is the extension flag. For single byte parameters, the extension flag is 0. In multibyte parameters, the extension flag is 1 in all bytes, except the last byte where it is 0. Bit 5 of the first byte is the sign bit, if equal to 0 then the integer is non-negative and if equal to

1 then the integer is negative. Bits b4 through b1 are the data bits of the first byte parameter and bits b5 through b1 are the data bits of the other byte parameters. Bit 7=1, is the parameter flag and bit 8 is the parity or omitted bit. The format is as follows:

	b8							b1
First byte	x	1	e	s	b	b	b	b
Second or last byte	x	1	e	b	b	b	b	b

Encoding of parameter data using basic format

In the bitstream format, parameter data is encoded as a sequence of one or more bytes structured as follows: bit 8 is the parity bit (or omitted bit) in the 7-bit code chart, b7=1 is the parameter flag. Bits b6 through b1 are the data bits of the parameter, the format is as follows:

	b8							b1
First byte	x	1	b	b	b	b	b	b
Second or last byte	x	1	b	b	b	b	b	b

Encoding of parameter data using bitstream format

Bitstream data are packed in consecutive data bits starting from high-numbered bits to lower-numbered bits of the first byte for the most significant part of the bitstream data. The end of a bitstream format parameter cannot be derived from the bitstream format itself (the format is not self-delimiting). Instead, the end of the data (which shows the end of the bitstream format parameter) is identified by either the end of block code or upon receiving the next opcode that belongs to the next element. In the bitstream format, the X,Y coordinates parameter code bytes are encoded as unsigned absolute binary fractions.

Since the origin of the screen is defined at its lower left hand corner, absolute coordinates can never be negative and thus the sign bit which is used in the basic format is omitted and is used for data.

In geometric coding, the resolution of a terminal that displays the line diagram images is independent from the resolution of the received parameter data. Thus low to high terminal resolution can be used. If the resolution of the displayed terminal is different from the resolution of the received parameter data, then the terminal will truncate the coordinates to the required precision by adding or deleting the required number of zero's to the least significant data coordinates. If a resolution of 512x512 positions or pixels is used, then, using the bitstream format, the coordinates of each point will be encoded by three bytes.

3.4.3 Data Format of Geometric Drawing Elements in the Character Encoding

In this section, the data format of graphical elements in the character encoding used in this work to describe an image is given. The following assumptions have been made in the use of character encoding;

a) Both opcode and parameter code bytes have been represented by the 7-bit code chart. This means that bit 8, which is the parity check, is omitted. It is planned to use some other types of error correction or detection that are suitable for the fading mobile channel conditions.

b) Five graphical elements (Line, Polygon, Marker, Rectangle and Text) which use single-byte opcode are used to cover most of the drawing instructions required to represent line diagram images. Table1 indicates the opcodes used with single-byte opcode format.

c) For encoding parameter data, the bitstream format is used. The advantage of using bitstream format over the basic format is that the extend bit and sign bit of the basic format are available as data in the bitstream format. This means that more bits per code byte are used in the bitstream format than are used in the basic format. For example, in the bitstream format, 6 data parameter bits are encoded in one byte, while in the basic format 4 or 5 data parameter bits are encoded in one byte. In this work it is assumed that the coordinates of each point are encoded by three bytes using the bitstream format, which means a resolution of 512 x 512 positions or pixels. The first byte contains the three most significant bits of both X and Y coordinates and the last (third) byte contains the last three significant bits (where the 9 bits gives 2^9= 512 positions or pixels resolution) as follows;

1	x1 x2 x3 y1 y2 y3
1	x4 x5 x6 y4 y5 y6
1	x7 x8 x9 y7 y8 y9

↓ Decreasing significance of bits

Coding of coordinates using bitstream method

d) In a graphical element, a certain number of parameter code bytes may follow the opcode until another opcode, SI or SO code is recognized. The SI and SO codes are control codes used in the text element and will be described later.

In the following, the data format of the graphical elements being used in this work and the number of parameter code bytes assigned with each element are given as follows;

Line

The line graphical element is used to draw a line between two points or more. The element consists of the POLYLINE opcode (0100000) followed by a number of parameter data required to represent the X, Y coordinates of the following points. The direction and length of a line is specified by the end points. To draw a line between two points using an X, Y resolution of 512 x 512 positions or pixels a line element of (1 byte opcode + 6 bytes parameter data = 7 bytes) is required. The structure of the line element is as follows;

0	Polyline opcode,1 byte 0100000
1	Coordinate of the first point 3 bytes
1	Coordinate of the second point 3 bytes

Sequence of code bytes to draw a line with two points

If a line between three points is required then the total required code bytes will be 10 bytes, where each point requires three code bytes. The minimum code bytes used in a line graphical element is 7 code bytes, which is the case to draw a line between two points. The maximum bytes assumed is the case of a line of 6 points, which means an element of 19 code bytes.

Marker

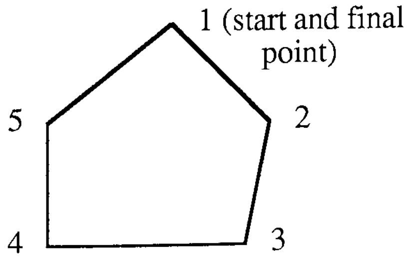
The marker graphical element is used to perform the basic geometric graphical operation, that of establishing the coordinate at which to commence drawing and drawing a marker. The marker graphical element format is similar to the line graphical format. It consists of the POLYMARKER opcode (0100010) followed by the parameter data to specify the X, Y coordinate of the drawing markers. A series of coordinate positions following a POLYMARKER opcode may be used to draw a marker by marker graph. The minimum code bytes used in a marker drawing element is 4 code bytes, which is the case of drawing one marker only. The maximum bytes used is assumed to be 19 which is the case of drawing 6 markers.

Rectangle

The rectangle graphical element provides the capability of drawing a rectangular area. The element consists of the RECTANGLE opcode (0101010) followed by parameter data that specify the coordinates of the first-corner (X1, Y1) and the second-corner (X2, Y2) of the rectangle. Thus a rectangle shape is specified by 1 byte rectangle opcode followed by 6 bytes of parameter data which represent the coordinates of the two corners, and the total is equal to 7 bytes.

Polygon

The polygon graphical element provides the capability of drawing a general polygonal area with specified vertices. The polygon element consists of the Polygon opcode followed by a series of X, Y coordinates of the following vertices. Fig. 3.2 shows the sequence of code bytes within a polygon element used to describe a five point polygon. At three bytes per coordinate plus an extra byte for the opcode the total amount of data required to describe or store the polygon is 3 x 5 +1=16 bytes. The minimum code bytes used in a polygon element is 10 bytes, which is the case of drawing a polygon shape of three points and the maximum code is 19 bytes, which means a polygon shape of 6 points.



A five point polygon

Bit 7	bit 1
0	POLYGON opcode, 1 byte
1	Coordinate of point 1, 3 bytes
1	Coordinate of point 2, 3 bytes
1	Coordinate of point 3, 3 bytes
1	Coordinate of point 4, 3 bytes
1	Coordinate of point 5, 3 bytes

Fig.3.2 Sequence of code bytes required to describe a five point polygon.

Text Format

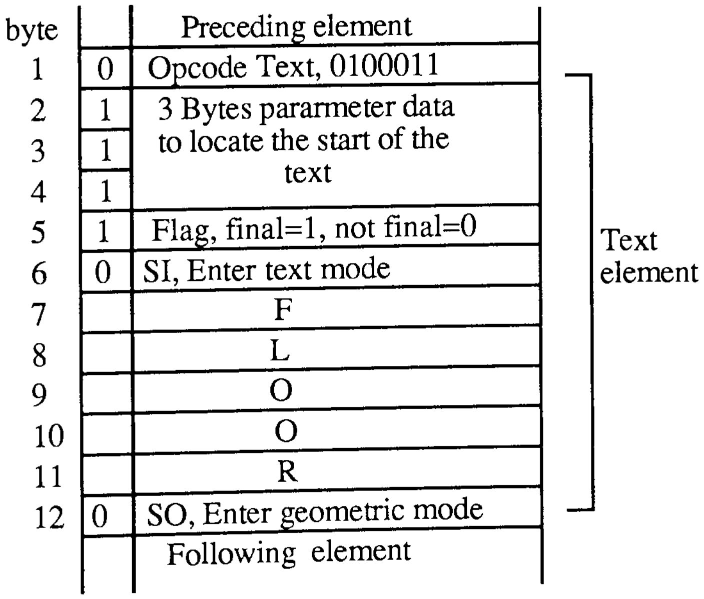
The character encoding has been developed by the ISO sub-committee responsible for encoding string character sets. The encoding conforms to the rules of the 7-bit ISO 646 or the code extension specified in ISO 2022 in the category of a complete coding system. The British Standard BS 4730 equivalent to the 7-bit ISO 646 is used for text representation in this work [85]. This standard specifies a character set for general use in the UK, including control characters, letters, digits, punctuation signs and other symbols. The standard makes provision for the direct representation of 128 characters, each represented by a 7-bit pattern. Table 3.3 shows the UK 7-bit code table used for text representation.

Table 3.3 The UK 7-bit code table for text representation

				b7 b6 b5	0 0 0	0 0 1	0 1 0	0 1 1	1 0 0	1 0 1	1 1 0	1 1 1
b4	b3	b2	b1	Col Ro.	0	1	2	3	4	5	6	7
0	0	0	0	0	NUL	DLE	SP	0	@	P	`	p
0	0	0	1	1	SOH	DC1	!	1	A	Q	a	q
0	0	1	0	2	STX	DC2	"	2	B	R	b	r
0	0	1	1	3	ETX	DC3	£	3	C	S	c	s
0	1	0	0	4	ETO	DC4	$	4	D	T	d	t
0	1	0	1	5	ENQ	NAK	%	5	E	U	e	u
0	1	1	0	6	ACK	SYN	&	6	F	V	f	v
0	1	1	1	7	BEL	ETB	'	7	G	W	g	w
1	0	0	0	8	BS	CNA	(	8	H	X	h	x
1	0	0	1	9	HT	EM	)	9	I	Y	i	y
1	0	1	0	10	LF	SUB	*	:	J	Z	j	z
1	0	1	1	11	VT	ESC	+	;	K	[	k	{
1	1	0	0	12	FF	IS4	,	<	L	\	l	|
1	1	0	1	13	CR	IS3	-	=	M	]	m	}
1	1	1	0	14	SO	IS2	.	>	N	^	n	-
1	1	1	1	15	SI	IS1	/	?	O	_	o	DEL

The 128 bit combinations of the UK 7-bit code table represent control characters (C0) and graphic characters (G-sets). The C0 characters occupy columns 0 an 1 of the code table. In general the C0 sets are used to control the shape and type of the G-sets. The G-sets are coded character sets of 94 characters designated to represent text information in the CGM [57]. The G-sets are invoked into columns 2 through 7 of the UK 7-bit code character. Strings are coded as sequences of bytes, starting with Open Character String (OCS) code and terminated by String Terminator (ST) code. The OCS and ST characters are coded by two code bytes. In this work we shall consider the single code control character SI (0/15) and SO (0/14) to replace the OCT and ST characters respectively. The SI control character is the enter text code. It establishes the code chart for encoding string text characters only. The SO control character is the exit text code. It establishes the code chart for encoding the graphics elements only.

The format of a text element is best shown by an example. Fig. 3.3 shows the sequence of code bytes within a text element required to draw the word (FLOOR) at the position of X=0.5, Y=0.5 of the display, where the maximum display is X=1 and Y=1.



byte		Preceding element
1	0	Opcode Text, 0100011
2	1	3 Bytes pararmeter data to locate the start of the text
3	1	
4	1	
5	1	Flag, final=1, not final=0
6	0	SI, Enter text mode
7		F
8		L
9		O
10		O
11		R
12	0	SO, Enter geometric mode
		Following element

Fig. 3.3 Code bytes within a text element to draw the word FLOOR

The flag code byte is used to instruct the receiver if the text to be drawn is final or not. The required number of code bytes data to draw the word "FLOOR" using character encoding is 12 code bytes. The maximum number of strings within a text is assumed to be equal or less than 20.

3.4.4 The Line Diagram Test Images

In order to study the effect of the fading mobile communication channel on transmitted image data, it is necessary to consider a specific line diagram image as a test image. For this purpose, two line diagram images are considered based on the assumptions we have made. The first test image is the 4th-floor north-wing plan at Aston University and the second test image is the Aston University campus map as shown in Figures 3.4 and 3.5 respectively. The contents of the test images consist of geometric drawing elements of Line, Polygon, Rectangle and Text elements. Fig. 3.4 consists of Line and Text elements and Fig. 3.5 consists of Line, Polygon, Rectangle and Text elements.

A computer program using the GKS graphic system, which is based on geometric codes and operates on the main frame computer of the Aston University, is used to represent the two line diagram test images. For each line diagram test image, an image file is stored in computer. The file contains data in a form of code bytes required to describe the drawing elements of the line diagram test image. To represent a line diagram test image by computer, the program calls the stored image file data for the required test image, processes the image file data and then reproduces the test image either as a display image on the computer screen or as computer graphic plot using the graphic plotter. The facility of the Tektronics laboratory at the Aston University has been used to process and reproduce the line diagram test images. The computer program reproduces the test images as follows.

The program calls the stored image file data of the specified test image and starts from the beginning of the image file searching for the first received opcode of a geometric drawing element to initiate a start. When the first opcode is obtained, the program starts reading the code bytes following the first opcode as parameter data of the first opcode. After several parameter code bytes the program obtains the next opcode belonging to the next element. At this stage the program completes the reception of the first element and the number of the code bytes for the first drawing element is defined. The next step is to reproduce the shape of the drawing element. For this purpose, the GKS graphic system is used to process the data of the drawing element and reproduce its shape. Then the program starts to define the number of code bytes for the next drawing element and reproduce its shape. This operation is continued up to end of the image file, where the final shape of the test image is reproduced.

The amount of data required to store the two test images in a computer graphics metafile using character encoding is shown in Tables 3.4 and 3.5. The amount of data of each image is 501 bytes and 1085 bytes respectively. In character encoding, bit 8 of each code byte is used for parity check. This parity check may be deleted when using other error control schemes (as will be described in later chapters). Thus the image file size will become 501 x 7 = 3507 bits for test image 1 and 1085 x 7 = 7595 bits for the test image 2 respectively. The data represents the image file size to be transmitted through a mobile channel.

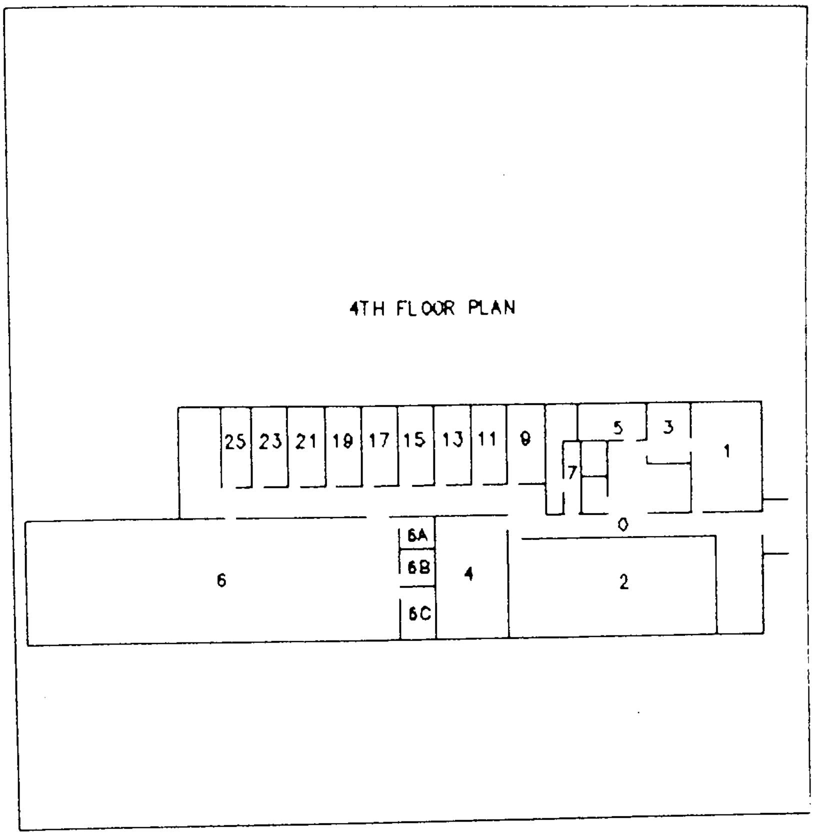


Fig. 3.4 The 4th-Floor North-Wing plan at Aston University represented as test image 1

Fig. 3.5 The Aston University campus map represented as test image 2

Table 3.4 Code bytes required by character encoding method to store the 4th-floor north-wing test image in a computer graphics metafile

Elements	Code bytes per element	Total elements	Total code bytes/elements
OPCODE: POLYLINE	1	36	36
Parameter data X, Y coordinates	3	91	273
OPCODE: TEXT	1	21	21
< Text: starting point >	3	21	63
< Text: final or not >	1	21	21
< String: start >	1	21	21
< Text: text display >	1	45	45
< String: end >	1	21	21
		Total =	501 Bytes

Table 3.5 Code bytes required by character encoding method to store the Aston University campus map test image in a computer graphics metafile

Elements	Code bytes per element	Total elements	Total code bytes/elements
OPCODE: POLYLINE	1	37	37
Parameter data X, Y coordinates	3	126	378
OPCODE: POLYGON	1	40	40
Parameter data X, Y coordinates	3	165	495
OPCODE: RECTANGLE	1	2	2
Parameter data X, Y coordinates	3	4	12
OPCODE: TEXT	1	12	12
< Text: starting point >	3	12	36
< Text: final or not >	1	12	12
< String: start >	1	12	12
< Text: text display >	1	37	37
< String: end >	1	12	12
		Total =	1085 bytes

3.5 Summary

In this chapter, low bit-rate image data for transmission over conventional digital networks or a PSTN involving mobile terminal was discussed. A source code known as character encoding based on geometric codes was proposed for describing line diagram images. The advantage of character encoding is that the amount of data required to describe an image depends on the image details. Thus a simple image requires a small amount of data for storage or transmission. This feature is important when considering the transmission of image data over low bit rate channels such as mobile channels. In character encoding, the resolution of the reproduced images depends on the terminal resolution. Thus, reproduced images of low to high resolution can be obtained.

CHAPTER 4

MOBILE RADIO CHANNEL MODELLING

4.1 Introduction

In chapter 3 the amount of data required to store test images 1 and 2 in a computer graphics metafile was determined. The next step is to transmit the image file data over digital networks, such as a local area network or ISDN, in combination with a mobile terminal. The effect of transmission errors on the image data is expected to be serious and is therefore considered in detail in this chapter. It is generally accepted that the quality of the transmitted signal in a mobile channel is much poorer than in a conventional digital network. A transmission system that works acceptably well over mobile channels should therefore perform equally well over conventional digital networks. For this reason we shall consider only the effect of errors due to mobile transmission on the transmitted image data.

To determine the effect of mobile transmission errors on the transmitted image data, an error source representing the characteristics of the mobile channel in various environments is required. The error source information is usually recorded or stored in computer files ready to access for use in the assessment of the transmitted data quality. The common methods used to define an error source are based on field measurements or channel modelling. In this study, the error source is generated using mobile channel modelling.

In this chapter the characteristics and modelling of a mobile radio channel are presented. Section 4.2 briefly mentions characteristics of the mobile radio channel. Section 4.3 deals with the mobile channel modelling. In section 4.4 the bit error statistics of the modelled mobile channel are presented. Finally, a summary is given in section 4.5.

4.2 Mobile Radio Channel Characteristics

The mobile radio channel characteristics are subject to various disturbances. The primary effect is the radio frequency propagation attenuation. The greater the distance between transmitter and receiver, the greater the path loss. Thus the power of the base station, the antenna height, and the frequency of the transmission will together define a coverage area within which a receiver will receive an adequate signal. Within the coverage area, different mobile users will receive a different quality signal, from best around the base station, to worst at the perimeter. Other variations in signal quality result from local topological features. These include hills, buildings and trees, as well as moving objects such as vehicles. These features tend to dissipate propagated energy, reducing the received signal level at the mobile and also at the base station. Thus users can expect to experience signal quality variations as they move past topographical features or as features move past the user [32, 33].

In addition, mobile radio signals are also affected by various types of scattering and multipath interference which can cause severe signal fading. Fading has two primary causes: these are multipath and shadowing interference. The most serious cause of interference is due to multipath received signals. In multipath, many of the topological features between the transmitter and the receiver do not simply attenuate radio signals, they also reflect them, see Fig.4.1. The input to the receiver may include a direct path and one or more reflected paths. Small variations in each path length can result in large phase differences between signals at the receiver. When multipath signals arrive at the receiver out of phase with each other, cancellation can occur. Therefore, a wave pattern of peaks and nulls is produced according to the phase differences at the receiver. A vehicle moving through this pattern passes alternately through peaks and nulls, resulting in the rapid signal variation known as short term multipath fading. Short duration fades of a depth less than 20 dB below the average signal level are frequent and deeper fades up to of 30-40 dB are also observed, see Fig.4.2. Rapid fading is usually observed over short

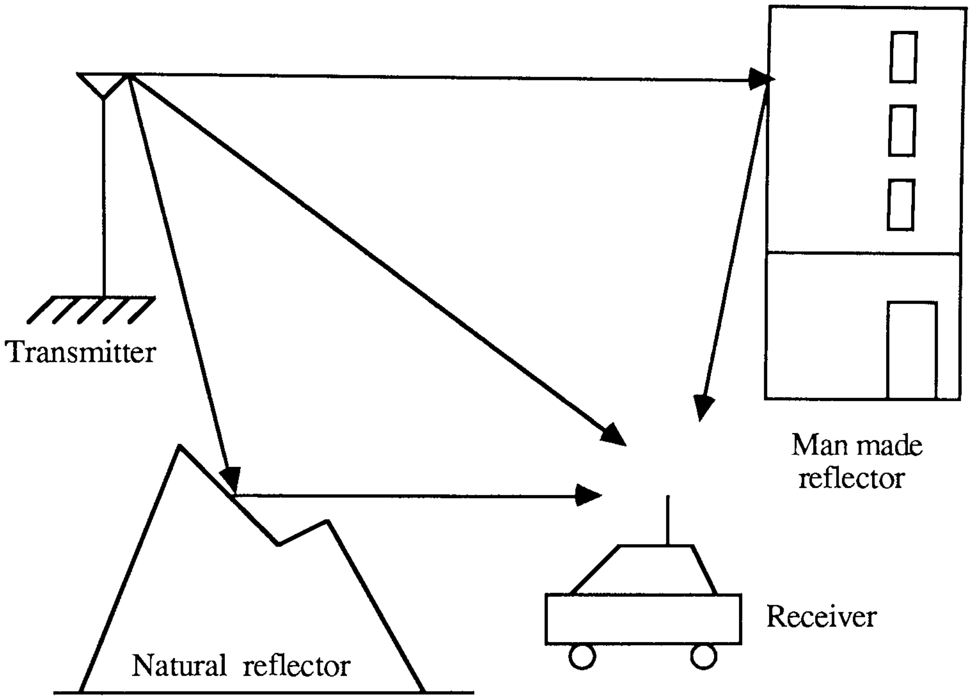


Fig. 4.1 Multipath phenomenon in mobile radio channels

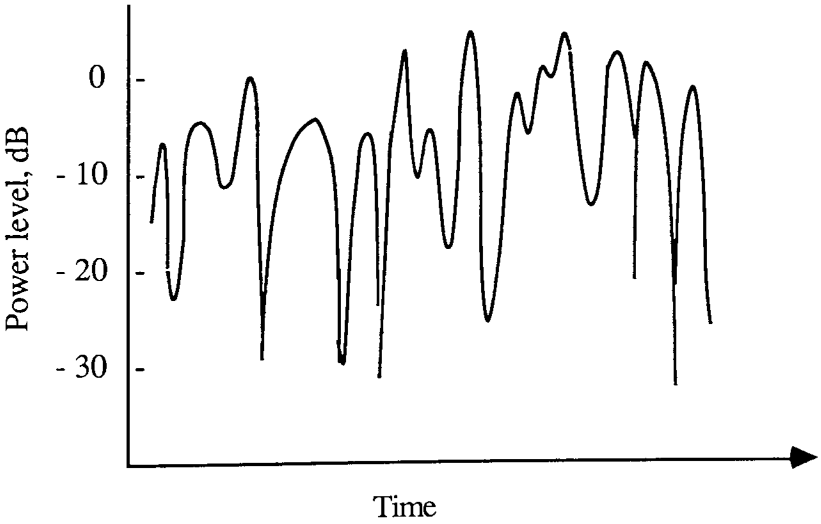


Fig. 4.2 Typical fading signal strength in mobile radio channels

distances of about half wavelengths. When fades occur it causes any digital data transmitted to be corrupted with a burst of errors. The length of this burst depends on the duration of the fade, which is in turn a function of the signal level, the mobile speed and the frequency of the carrier. Many authors have shown that the amplitude distribution of a short term multipath signal can be approximated very closely by a Rayleigh distribution [32-38].

The characteristics of the multipath fading changes as the mobile passes a large building or travels under a bridge. Under such conditions, the rapid multipath fades are superimposed on a signal of slowly varying level. This phenomena is known as long term multipath fading caused by shadowing. The mean value variations of the received signal caused by shadowing effects are found to be lognormally distributed [36, 98].

Thus, in a typical mobile radio propagation situation, the received signal will show fading consisting of very rapid fluctuations due to short term multipath phenomena superimposed on relatively slow variations of the mean level due to shadowing. In mobile channel modelling, the mean value of the received signal is usually assumed to be constant so the distribution of the received signal can be represented by a Rayleigh distribution. This is because the characteristics of the multipath short term represented by the Rayleigh distribution places the most severe limits on the transmitted signal quality.

Field measurements have revealed that random errors are also observed on mobile channels but with a small probability of occurrence in comparison to errors that occur during fading [59, 60]. It is to be expected, therefore, that data transmission over mobile channels will suffer from two source of errors, fading, which produces long bursts of errors, and random errors. The effect of fading is much more serious and is considered to be the major source of errors.

4.3 Mobile Radio Channel Modelling

To determine the effect of mobile transmission errors on the transmitted image data, an error source representing the characteristics of the mobile channel in various environments is required. The error source information is usually recorded or stored in a computer file ready to access for use in the assessment of the transmitted data quality. The error source is also used to determine and analyse the error statistics of the channel, which are useful when considering suitable error control schemes.

A common method used to obtain the mobile error source is based on field measurements, where a continuous data signal is transmitted from a base station to a mobile moving over various routes and under various mobile transmission conditions. At the mobile, the received signal is demodulated and the data is compared with the regenerated reference transmitted data. The resulting error sequence pattern is recorded for a certain required time and may be then stored in a computer file ready for use [58-61].

In a situation where the field measurement is not easily available, the error source can be represented by fading channel modelling [62, 63]. Although modelling the mobile suffers from certain shortcomings compared to field measurements, it can be used successfully to estimate fading rates and average fade and nonfade duration. These characteristics can then be used to represent and model the channel. The channel modelling is best used on a relative basis, rather than as absolute measures of performance. It can be used to compare different error control schemes applied to mobile channels or to test the performance efficiency of various systems. It should be emphasised that sample results of channel modelling must be compared with field test measurements to be sure that the performance of the model is satisfactory [58-61].

The simplest channel model in information theory is the binary symmetric channel, where errors are considered statistically independent. This model corresponds to the memoryless channel with additive Gaussian noise. The model is completely described by a single parameter, the probability of error P_e. This model is usually used for channels where errors occur randomly, as for example, in space links.

In mobile radio environments, the strength of a received signal varies randomly with a Rayleigh distribution. If g is the instantaneous signal-to-noise power ratio, then this will be a varying quantity on account of the effect of the fading. The probability density function P(g) of the signal-to-noise ratio (SNR) is given by [99] ;

$$\begin{aligned} P(g) &= \left(\frac{1}{g_o}\right) . \exp\left(\frac{-g}{g_o}\right) && g \geq 0 \\ P(g) &= 0 && g < 0 \end{aligned} \tag{4.1}$$

where, g_o = Mean signal-to-noise ratio (SNR)

The bit error probability $P_e(g)$ for a constant signal-to-noise ratio for binary non-coherent frequency-shift-keying (NCFSK) is given by ;

$$P_e(g) = \frac{1}{2} . \exp\left(\frac{-g}{2}\right) \tag{4.2}$$

To obtain the bit error probability P_e in the fading channel we average $P_e(g)$ over the probability density function P(g);

$$P_e = \int_0^\infty P_e(g) . P(g) . dg = \frac{1}{2 + g_o} \tag{4.3}$$

It is clear that the fading causes a severe degradation of the bit error performance of the system as it decreases linearly with increasing average SNR. The equation for P_e is not adequate for describing mobile channels. The difficulty with this expression is that it is based on the assumption that the errors occur independently (randomly), whereas errors over mobile channels occur in a mixture of burst and random patterns. Channel models that give randomly occurring errors are not suitable therefore for mobile channels.

In this study, a mobile channel model is presented that generates burst and random error patterns almost similar to the real channel case. The model is based on the description of fading phenomena on the digital mobile channel [66, 68-70, 100-103, 137]. We assume that fades occur due to short term multipath phenomena, so the Rayleigh distribution is valid for the strength of the received signal. The fading channel is considered to be in one of two states, a bad (fade) state, where the error probability is high, and a good (nonfade) state where the error probability is low, see Fig.4.3.

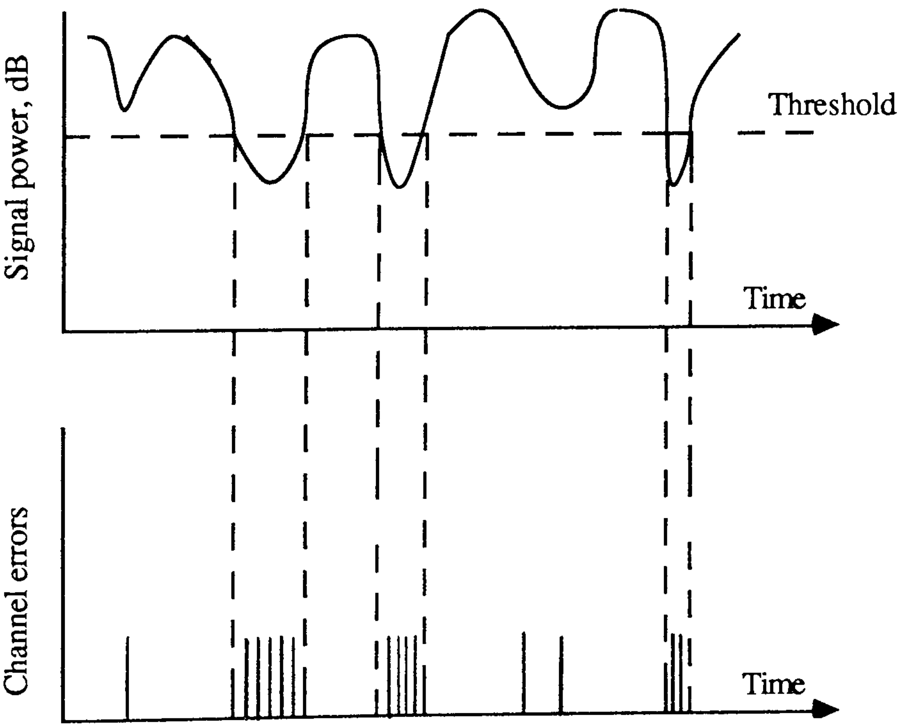


Fig. 4.3 Occurrence of errors over digital mobile channels

The fade state corresponds to the case where the signal falls below the threshold level of the receiver. During this time interval the fade causes any signal transmitted to be corrupted with a burst of errors. The length of these bursts depends on the duration of the fade, which is in turn a function of the mobile channel parameters such as vehicle speed. Therefore, the channel error probability is high for the duration of the fade. During the time the signal is above the threshold of reception the channel error probability drops to a very low value.

The fade and nonfade phenomena on the channel can therefore be represented best by a channel model having transitions between good and bad states. The two-state Markovian model known as the Gilbert-Elliott model [64-65] has been used extensively for modelling bursty channels [66, 67, 101, 104] and is proposed in this study for modelling mobile radio channels [105]. The model is a useful tool for the simulation of real channels with bursts of errors. Computer simulation is used for mobile channel modelling. A sequence of binary digits is generated digit by digit by the Markovin Gilbert-Elliott model representing the fade and the nonfade states. The generated binary digits are stored in a computer file known as the error file. Error files are files of binary sequences where digit 1 corresponds to an error digit and digit 0 to a correct digit.[95].

Before starting with channel modelling, we first introduce the important key parameters of the Gilbert-Elliott model. The model consists of two states (bad and good) with defined transition probabilities, see Fig.4.4.

The transitions between the states produce a state sequence which is a Markov chain. The model implies that transitions from one state to another occur at random. The transition sequence can be mapped to a digital sequence representing the error sequence of the error source. The transition probabilities are P=Prob(G-B), probability of change from good state to bad state, and p=Prob(B-G), probability of change from bad state to good state. In each state an error source sequence is generated using a binary symmetric channel model. In the bad state, the error probability is P_b and, in the good state, the error probability is P_g, where P_g is much smaller than P_b.

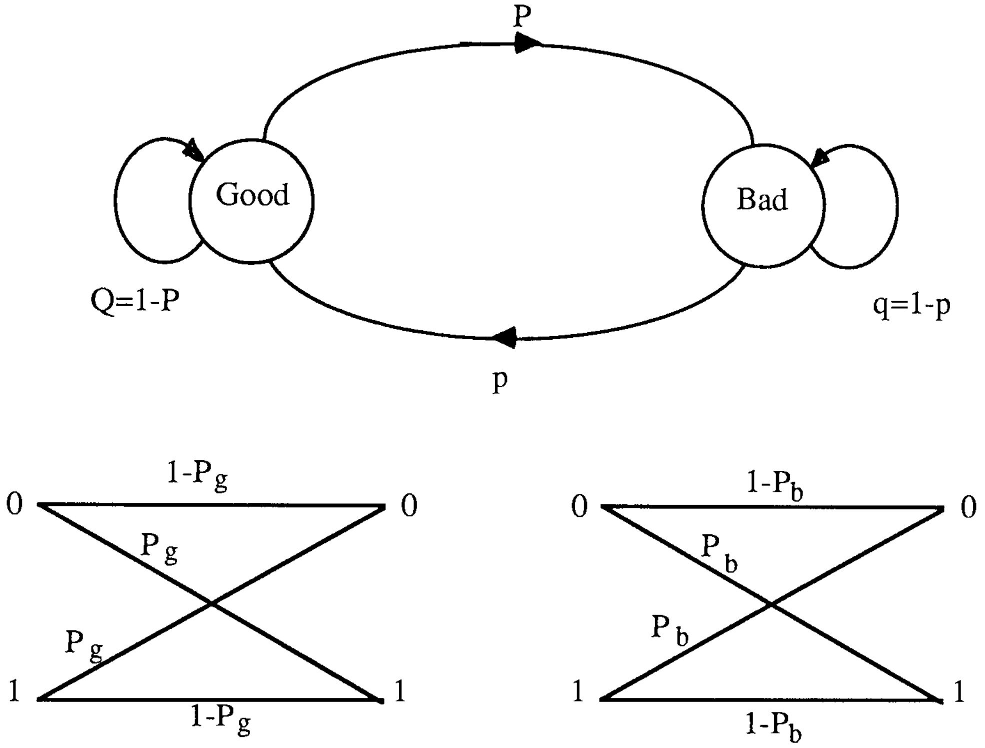


Fig. 4.4 The Gilbert-Elliott model for mobile channel modelling

In the Gilbert model, the probability of error in the good state P_g is zero. In the bad state the error probability P_b is relatively high (e.g., 0.5), which corresponds to the burst noise. The transition probabilities P and p are small, such that the probabilities Q=1-P and q=1-p of persisting in the good and bad states are high. Elliott suggested a modification to Gilbert's model by assuming a small value of error probability in the good state. In this way it would be possible to visualize channels as making transitions between long periods of good state with small background probability of error and burst error state with relatively larger probability of error.

For the Gilbert-Elliott model, let B_s denote the number of consecutive bits in a bad state following a given good state and G_s the number of consecutive bits in a good state following a given bad state. The mean values of these random variable run lengths are calculated to be [64] :

$$E(B_s) = \frac{1}{p} \qquad E(G_s) = \frac{1}{P} \tag{4.4}$$

The channel modelling starts by relating the transition states of the Gilbert-Elliott model to the fade and nonfade states of the Rayleigh fading mobile channel. To do this we need a knowledge of the times when the mobile channel makes a transition from the good (nonfade) to the bad (fade) state or vice-versa, as well as the length of time that the channel stays in the newly acquired state. The average fade duration $E(t_b)$ below the threshold level in a Rayleigh fading environment is given by [32-36]:

$$E(t_b) = \frac{\exp(\rho) - 1}{f_d \, . \, (2.\pi.\rho)^{1/2}} \tag{4.5}$$

The average number of fades which go below the threshold level (level crossing rate) is given by;

$$\text{Fade Rate} = \exp(-\rho) \, . \, f_d \, . \, (2.\pi.\rho)^{1/2} \tag{4.6}$$

The average nonfade duration $E(t_g)$ above the threshold level is given by :

$$E(t_g) = \frac{1}{f_d \, . \, (2.\pi.\rho)^{1/2}} \tag{4.7}$$

Where: $\rho = g_{th} / g_o$

g_{th} = Threshold power level

g_o = Average received signal-to-noise ratio SNR

$f_d = V / \lambda$ = Doppler frequency

V = Mobile vehicle speed in MPH

λ = Wave length of the transmitted carrier frequency

The average fade and nonfade duration times given are for the analogue mobile channel. To generate digital error sequence bits we have to relate these times to the number of bits which fall in the bad and good states. The required number of bits are determined by dividing the average times by the bit duration T. Thus, the average number of bits in the fade $E(n_b)$ and the nonfade $E(n_g)$ periods are given by;

$$E(n_b) = \frac{E(t_b)}{T} \qquad E(n_g) = \frac{E(t_g)}{T} \tag{4.8}$$

where: T = 1 / R = Bit duration in seconds.

R = Transmission rate in bits/s.

We assume only integral numbers of bits fall within either the good or bad states.

To determine the transition probabilities p and P we let the average number of consecutive bad $E(B_s)$ and good $E(G_s)$ states in the Gilbert-Elliott model be equal to the average fade and nonfade duration, normalized with the bit time interval T. Therefore;

$$E(B_s) = \frac{E(t_b)}{T} = E(n_b)$$
$$E(G_s) = \frac{E(t_g)}{T} = E(n_g) \qquad (4.9)$$

Hence, the transition probabilities p, P are given by;

$$p = \text{Prob}(B\text{-}G) = \frac{1}{E(B_s)} = \frac{f_d .T .(2.\pi.\rho)^{1/2}}{\exp(\rho) - 1} \qquad (4.10)$$

$$P = \text{Prob}(G\text{-}B) = \frac{1}{E(G_s)} = f_d \,.\, T .(2.\pi.\rho)^{1/2} \qquad (4.11)$$

The next step is to obtain the error probabilities in the bad and good states. The bad (fade) state represents the case when the signal value is below the receiver threshold. For modelling the mobile channel, a maximum value of error rate below threshold level P_b= 0.5 is assumed [44, 67, 98]. Thus, during the fade periods, the probability of receiving a digit in error is very high, which means errors occur in burst patterns.

The good state represents the case when the signal value is above the receiver threshold level. The probability of bit error when the signal is above the threshold is given by [66, 101];

$$P_g = \frac{1}{2+g_o} \,.\, \exp\left(\frac{-g_{th}}{2}\right) \qquad (4.12)$$

Equation (4.12) shows that the probability of bit error depends on the signal level and the receiver threshold level. For normal values of signal and receiver threshold levels the value of P_g is very small in comparison to P_b in the fade state. This indicates that errors occur randomly in the good state.

At this stage the equations relating to fading channels and their relationships to the Gilbert-Elliott model have been presented. The next step is to generate the error sequence digit by digit for the fade and nonfade states and store the digits in the error file. Computer simulation is used to generate the error sequence.

Computer Simulation

In order to produce error files we must know the statistical distribution of the fade and nonfade duration times on the mobile channel representing bad and good states. There is general agreement on the fade time statistics, which follow an exponential distribution [37, 106]. The nonfade duration statistics are found to be a function of the chosen threshold level. It has been shown [69] that, for a threshold of -10 dB or lower relative to the mean signal to noise ratio, the nonfade duration statistics can be approximated by an exponential distribution. In this work simulations are carried out for a threshold level of -10 dB, so the exponential model for the nonfade distribution is valid. For the Gilbert-Eillott model, it can be shown that, for relatively stable good and bad states, the time statistics of the states also follow an exponential distribution. In the model the transition probabilities P and p are assumed small, such that the probabilities Q=1-P and q=1-p of persisting in the states are high. Under such conditions, the probability that the channel stays in the good state P_{good} for not less than $E(n_g)$ consecutive good bits, is given by [107];

$$P_{good} = [1-P]^{E(n_g)} \tag{4.13}$$

For small values of P, such that (1-P) is approximately equal to 1, equation (4.13) can be written as;

$$P_{good} = \exp(-P \,.\, E(n_g)) \tag{4.14}$$

The computer simulation for the channel modelling starts with the assumption that at the beginning the channel is in the nonfade (good) state, see Fig.4.5. Note that if the simulation is sufficiently long, as it should be, the initial state is unimportant. A uniformly distributed random variable (UDRV) number R_{gi} is generated by the computer representing the value of the P_{good} during the good state and is used to determine the number of bits in the nonfade duration on the basis of:

$$R_{gi} = \exp(-P.\,E(n_g)) \tag{4.15}$$

Thus:

$$E(n_g) = \left(\frac{-\ln R_{gi}}{P}\right) = \mathrm{INT}\left[\frac{-\ln R_{gi}}{f_d\,.\,T.\,(2.\pi.\rho)^{1/2}}\right] \tag{4.16}$$

where INT denotes the integer value of $E(n_g)$.

After the number of bits in the good state have been determined, each bit is examined to see whether it is in error or not. For this purpose, the channel is modelled as being binary symmetric, such that the probability of error is low in the good state and high during the bad state. In the good state the probability of error is P_g. Thus, to determine whether the received bit is in error or not, a UDRV is generated and the outcome is compared with the probability of correct reception $(1-P_g)$ during the good state. If the value of the generated number is less than $(1-P_g)$, then no error is counted. However, if the number is larger than $(1-P_g)$ then an error is counted. This operation is continued until all bits in the good state are simulated.

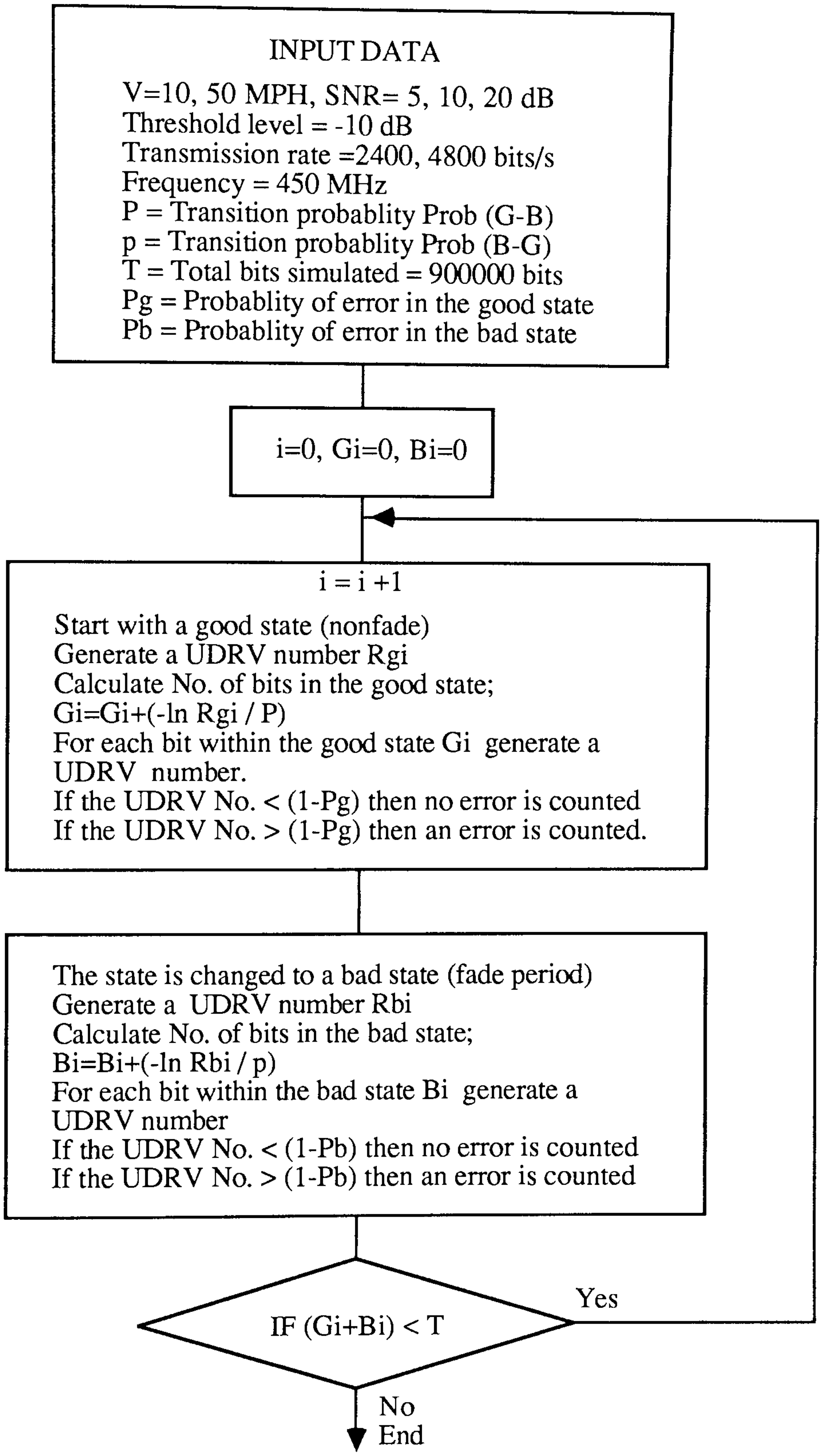


Fig. 4.5 Flow chart diagram for mobile channel modelling using the Gilbert-Elliott model

Since the good and bad states are always alternating, after determining the state of each bit in a good state, the channel must make a transition to a bad state. In this state, the error probability is high, P_b=0.5, and the transmitted data suffers a high error rate. A similar procedure is followed to determine which bits are received in error and which are error-free while the channel is in the bad state. In the bad state the number of bits in the fade period is given by :

$$E(n_b) = \left(\frac{- \ln R_{bi}}{p} \right) = \mathrm{INT} \left[\frac{(- \ln R_{bi}) . (\exp(\rho) - 1)}{f_d . T . (2.\pi.\rho)^{1/2}} \right] \qquad (4.17)$$

The final factor concerning the simulation is the length (i.e., the number of bits) of the generated error file. The length has to be sufficiently long to obtain statistically reliable simulation results. In the case of the binary symmetric channel (i.e., when errors are statistically independent), the total number of bits required is around 10 / P_e [108], where P_e is the error probability (bit error rate) under consideration. For example, for $P_e = 10^{-4}$, the length of the file is 10^5 bits. For the Gilbert-Elliott model, which can be conceived of as a chain of two binary symmetric channels, we have used more bits for the simulation. A total of about 900000 bits has been used for simulating the mobile radio channel and generating the error file. This number was chosen because it represents the limit of the computer file storage. This represents a transmission time of about 6.25 minutes for a 2400 bits/s transmission rate (i.e., 900000 / 2400x60 = 6.25). This time is considered sufficient to give reliable simulation results [60, 108].

A total of 12 error files were generated and stored in the computer for various mobile channel parameters such as signal-to-noise ratio, vehicle speed and transmission data rate. The selected channel parameters represent typical values used in mobile communications. Three values of signal-to-noise ratios were considered, 20dB, 10dB and 5 dB. Two vehicle speeds were considered, a low speed of 10 MPH and a high speed of 50 MPH. Finally, two values of transmission rates were considered, 2400 bits/s and 4800 bits/s. In all error files, a transmission frequency of 450 MHz and a threshold level of -10 dB were assumed. The generated error files were therefore as follows:

Error File 1 ; SNR = 20 dB, Vehicle Speed = 10 MPH, Transmission Rate = 2400 bits/s
Error File 2 ; SNR = 20 dB, Vehicle Speed = 50 MPH, Transmission Rate = 2400 bits/s
Error File 3 ; SNR = 20 dB, Vehicle Speed = 10 MPH, Transmission Rate = 4800 bits/s
Error File 4 ; SNR = 20 dB, Vehicle Speed = 50 MPH, Transmission Rate = 4800 bits/s
Error File 5 ; SNR = 10 dB, Vehicle Speed = 10 MPH, Transmission Rate = 2400 bits/s
Error File 6 ; SNR = 10 dB, Vehicle Speed = 50 MPH, Transmission Rate = 2400 bits/s
Error File 7 ; SNR = 10 dB, Vehicle Speed = 10 MPH, Transmission Rate = 4800 bits/s
Error File 8 ; SNR = 10 dB, Vehicle Speed = 50 MPH, Transmission Rate = 4800 bits/s
Error File 9 ; SNR = 5 dB, Vehicle Speed = 10 MPH, Transmission Rate = 2400 bits/s
Error File 10 ; SNR = 5 dB, Vehicle Speed = 50 MPH, Transmission Rate = 2400 bits/s
Error File 11 ; SNR = 5 dB, Vehicle Speed = 10 MPH, Transmission Rate = 4800 bits/s
Error File 12 ; SNR = 5 dB, Vehicle Speed = 50 MPH, Transmission Rate = 4800 bits/s

The error files were used as mobile channel error sources for evaluating the performance of the transmission of image data as described in the following chapters. The process of error generation on the channel is conceived of as a modulo-2 summation of the transmitted digital bit sequence and the error sequence generated by the channel error source (error file), as shown in Fig. 4.6. The various results obtained from error files were also used to analyse the bit error statistics of the mobile radio channel. The bit error statistics are given below. These statistics are useful in relation to the consideration of error control techniques, allowing their effectiveness in reducing the overall errors to be examined.

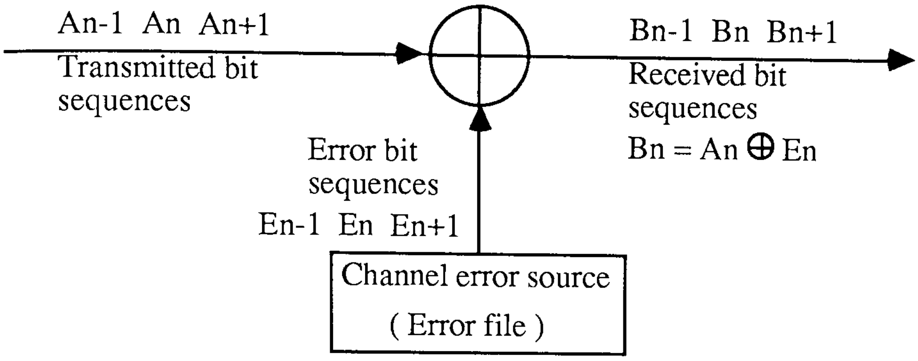


Fig. 4.6 The process of error generation on the mobile channel

4.4 Bit Error Statistics

The fading phenomena in the mobile channel results in bursty error patterns. The average channel bit error rate (BER), which is adequate to describe a channel with random errors, is therefore not adequate for the description of a mobile channel. For example, one burst of 20 error bits in an error-free sequence of 20000 bits is enough to hold the bit error-rate at 10^{-3}. The BER gives an indication of the error statistics but it does not contain information about how the errors occur. Thus, to describe the mobile channel adequately, statistics of the average bit error rate BER, the gap between errors, the error burst lengths, and the block error statistics are useful. These measures are used to present the bit error statistics in this thesis.

A) Average Bit Error Rate (BER)

The average BER is defined as the ratio of the total number of errors encountered from the error file to the total bits of the simulated error file (900000 bits). Error patterns obtained from the error files are closely related to the fade periods. The number of errors encountered during a certain period of time depends mainly on the periods of fades during this time interval. During the nonfade periods, the probability of errors is small for normal values of SNRs. The average BER encountered is the sum of errors in the fade and nonfade periods within the selected error file. A summary of the average BER against the received SNR for various error files is shown in Fig.4.7.

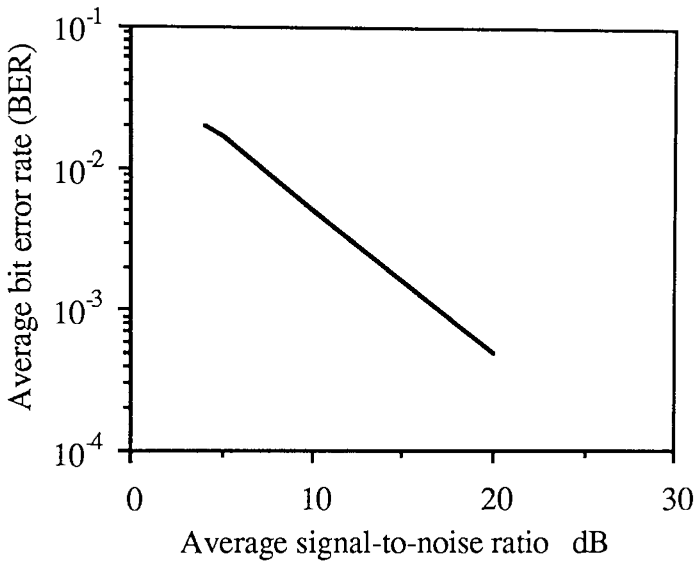


Fig. 4.7 The average bit error rate versus signal-to-noise ratio in mobile channels

It can be seen that the fading channel causes a severe degradation of the BER which decreases linearly with increasing average SNR. Figure 4.7 shows a decade drop in BER for a 10 dB rise in SNR, which is the same slope as for theoretical Rayleigh fading. In contrast, the decrease in average BER on a nonfading channel is exponential with SNR. This result, as expected, shows that the mobile fading channel is much poorer than other nonfading channels in terms of transmission errors.

The results obtained from error files have shown that the value of SNR is the critical factor in determining the BER. Other mobile channel parameters such as the vehicle speed and the transmission rate, have (very small) negligible effects. This is due to the fact that during a fixed period of time the product of the fade duration and the fade rate is constant for a fixed average value of SNR. However, we need to study the effect of transmission rates on the BER in more detail. At very low transmission rates, such as 100-200 bits/s or lower, the duration of a transmitted bit is much longer than the duration of the fades, so there are very few errors and transmission can be achieved successfully [43, 106, 109]. However, at such low rates the transmission efficiency is very low. The error-rate increases as the transmission rate is increased until the fades span many bits. At such rates the bit error-rate depends on the proportion of time for which the signal is in the fade state. For values of transmission rates of 2400 bits/s and 4800 bits/s used in the simulation, or higher rates, the fades generated cover many transmission bits. As the product of the fade durations and fade rates is constant for a fixed period of time and average SNR, the transmission rate will not affect the BER during fading. Thus, in mobile communications, it is best to use either low transmission rates or as high as the channel bandwidth allows. The transmission rates used in the simulation represent typical values that have been implemented for mobile data transmission [41, 48].

For values of SNR=20 dB (error files 1 to 4), SNR=10 dB (error files 5 to 8) and SNR=5 dB (error files 9 to 12), the corresponding average BERs are around 0.0005, 0.005 and 0.017 respectively. These values of BER which, as expected, are high compared to BERs of nonfading channels, are used to evaluate the performance of the transmitted image data in the following chapters. The BER results obtained from the computer simulation were compared with results obtained by experimental work [58, 60]. It was found that there is a good agreement between the two sets of results. For example, an average BER of 4×10^{-3} was obtained by field measurements conducted by French [60] at a SNR of 10 dB and other channel parameters similar to those used in the computer simulation. For the same conditions the average BER obtained by computer simulation was 5×10^{-3}, which does not differ widely from the value obtained by field measurements. For normal values of SNR, the results of the BER obtained by computer simulation and field measurements were found to be almost identical.

B) Error-Free Gap Distributions

An error-free gap is defined as that region of the observed error file data stream which begins with a correct bit that is immediately preceded by an error and ends with the last consecutive correct bit that is immediately followed by an error. For example, the data stream 100001 has an error- free gap of size four, where 1 represents an error and 0 a correct bit. The gap distribution is the plot of the cumulative frequency of the gap length versus the gap length. The gap distribution gives some indication of the randomness of the channel. The degree of randomness of the errors of an error file is determined by comparing the resulting cumulative gap distribution with the gap distribution of a random channel of the same average BER.

A computer program has been used to obtain the error-free gap distributions. Figures 4.8, 4.9 and 4.10 show the gap distributions for a mobile channel at SNR of 5 dB, 10 dB and 20 dB respectively. In each Figure, the distributions of three error files representing different mobile conditions are shown in addition to the distribution of a random error channel with an average BER value the same as for the mobile channel.

In comparing the results of the error-free gap distribution, it will be seen that a large number of short gaps occurs at the low vehicle speed of 10 MPH or low values of SNR, see Fig. 4.8. This is because, under such conditions, longer fade intervals occur, causing longer error bursts [58]. A large number of short gaps occur within the long error bursts. Some of the gap lengths, however, may be quite long, especially at low vehicle speed or high SNR, or both, see Fig. 4.10. This is due to low fade rates at low speed, which results in long fade and nonfade intervals, causing relatively short and long gaps. It is obvious that higher SNR increases the length of the error-free gap.

It can also be seen that the fading channel increases the average length of gaps compared to the random channel. The long lengths of error-free gap are of interest, since the distribution of these gaps indicates the amount of transmitted data that can be received without errors. At high vehicle speeds, relatively short periods of fade, but with high fade rates, occur. Under such conditions, and at a high value of SNR, the characteristics of the fading channel approaches the characteristics of the random error channel. see Fig.4.10.

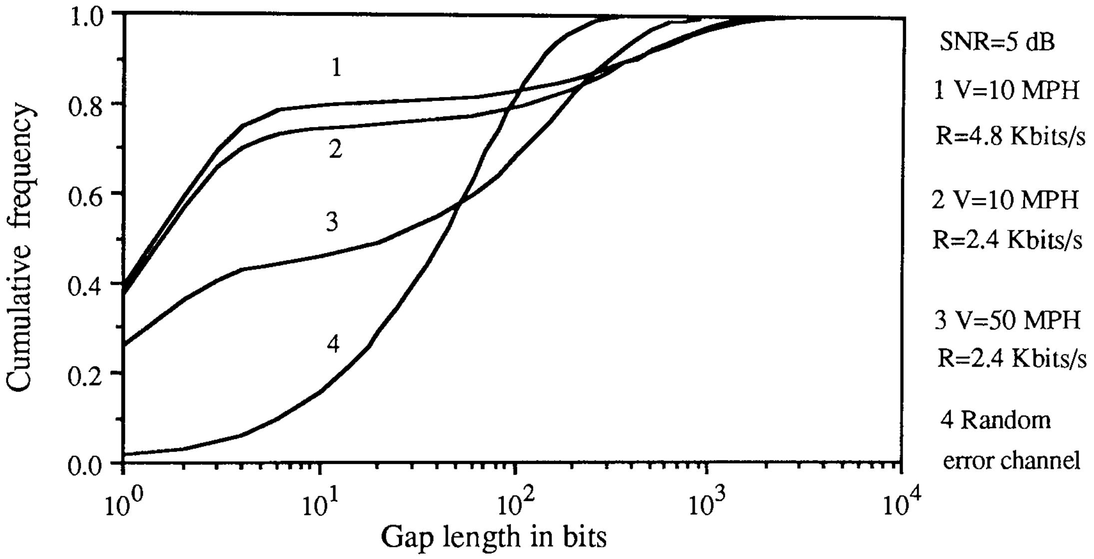


Fig. 4.8 Gap distribution for fading & random channels (BER = 0.017)

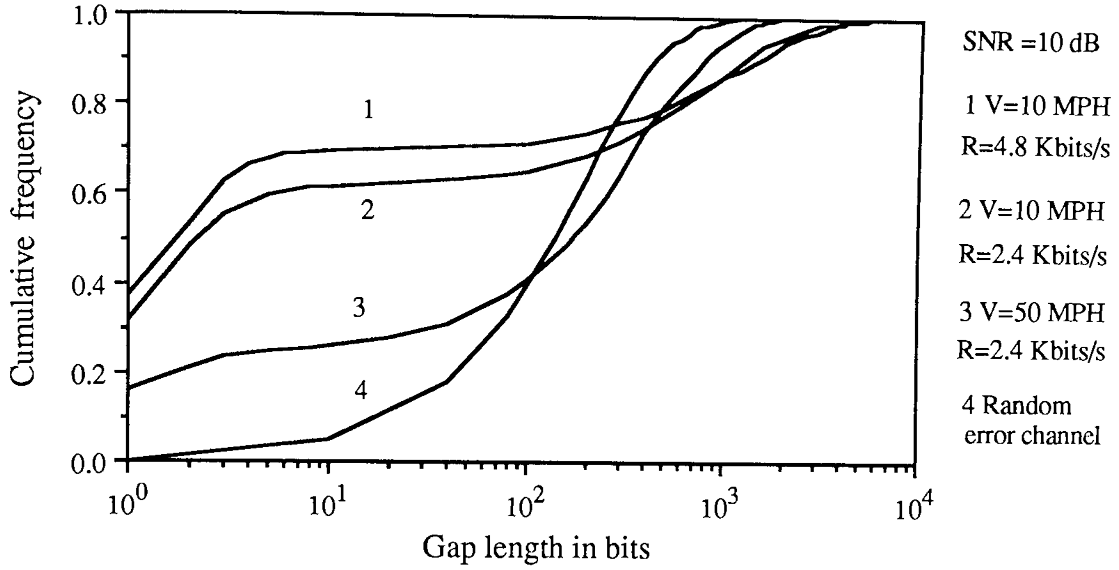


Fig. 4.9 Gap distribution for fading & random channels (BER = 0.005)

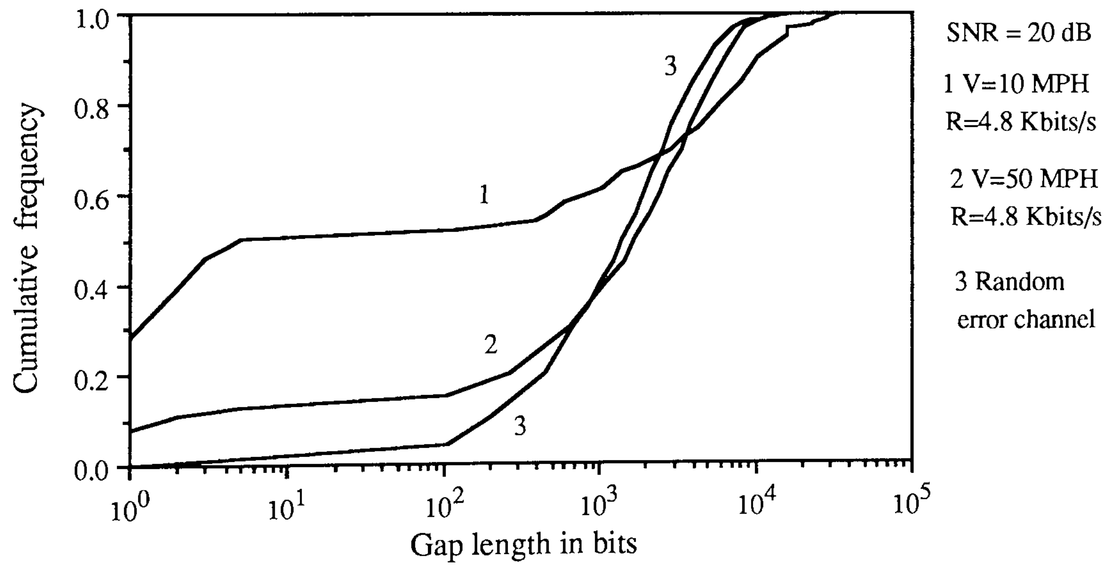


Fig. 4.10 Gap distribution for fading & random channels (BER = 0.0005)

C) Burst Distributions

A burst is defined as that region of the data bit stream within which at least two errors exist with a specified minimum density of errors Δ, where Δ is defined as the ratio of error bits to total bits in the burst region[132]. The region begins with an error bit that is preceded by a correct bit. A burst always ends with an error bit that is followed by a correct bit. The idea can be illustrated by an example. Let the specific density be Δ = 0.4 and consider the following sequence as an example;

0001001001001000001

Start from the first error. If the the second error is included the density is 2/4 =0.5. If the third error is included the density is 3/7 = 0.428; if the fourth error is included the density is 4 /14 < 0.4. Hence, the burst ends at the third error, i.e., 1001001, which is a burst of length 7 with the density larger than 0.4.

Based on the above definition of an error burst, the cumulative burst distributions of a mobile channel at SNR of 5 dB, 10 dB and 20 dB are calculated by computer for a burst density of Δ = 0.4 and are shown in Figures 4.11, 4.12 and 4.13 respectively. Since error bursts occur during fades, the average length of these error bursts is closely related to the average fade duration. Long error bursts are observed at low SNR or low vehicle speed [110]. At a transmission rate of 4800 bits/s, bursts about twice as long as those at 2400 bits/s are obtained [111]. From Figures 4.11, 4.12 and 4.13 it can be seen that long bursts of errors do occur under certain channel conditions. For example, at a SNR of 5 dB, a vehicle speed of 10 MPH and a transmission rate of 4800 bits/s (error file 11) over 20% of bursts are longer than 60 bits and 10% of the bursts are longer than 125 bits, see Fig.4.11. For the same channel conditions, error bursts of lengths up to 290 bits are obtained but with very small probability. For a transmission rate of 2400 bits/s and the same other channel parameters (error file 9) over 20% of the bursts are longer than 30 bits and 10% of the bursts are longer than 63 bits.

Shorter bursts are observed, as expected, at higher values of SNR or higher vehicle speed [112]. At a SNR of 10 dB, a transmission rate of 4800 bits/s and a vehicle speed of 10 MPH (error file 7) over 95% of the bursts are shorter than 70 bits, see Fig. 4.12. For a vehicle speed of 50 MPH and the same other channel parameters (error file 5) over 95% of the error bursts are shorter than 18 bits. Although shorter bursts are observed at a SNR of 10 dB, nevertheless, they are long enough to introduce errors in many transmission bits. It can be seen that at a SNR of 20 dB, comparatively short bursts are observed, see Fig. 4.13.

The burst distribution is an important factor in considering efficient error correction techniques for mobile communications systems. The distribution is also useful when considering the degree of interleaving required to disperse the errors in the burst to enable the errors to be treated as random when implementing error correcting code strategies.

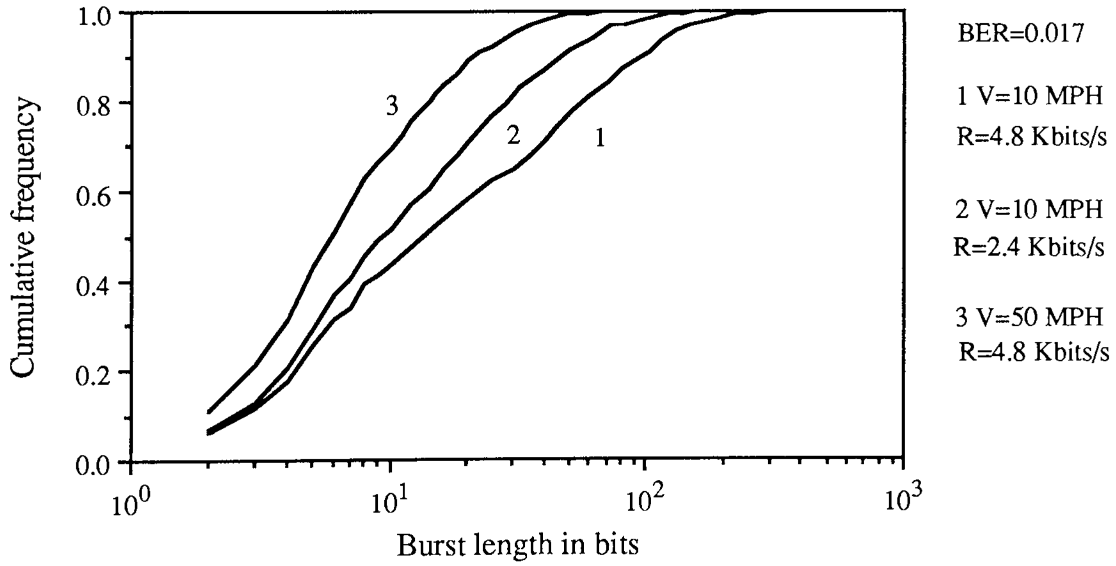


Fig. 4.11 Burst distribution for a fading channel at SNR = 5 dB

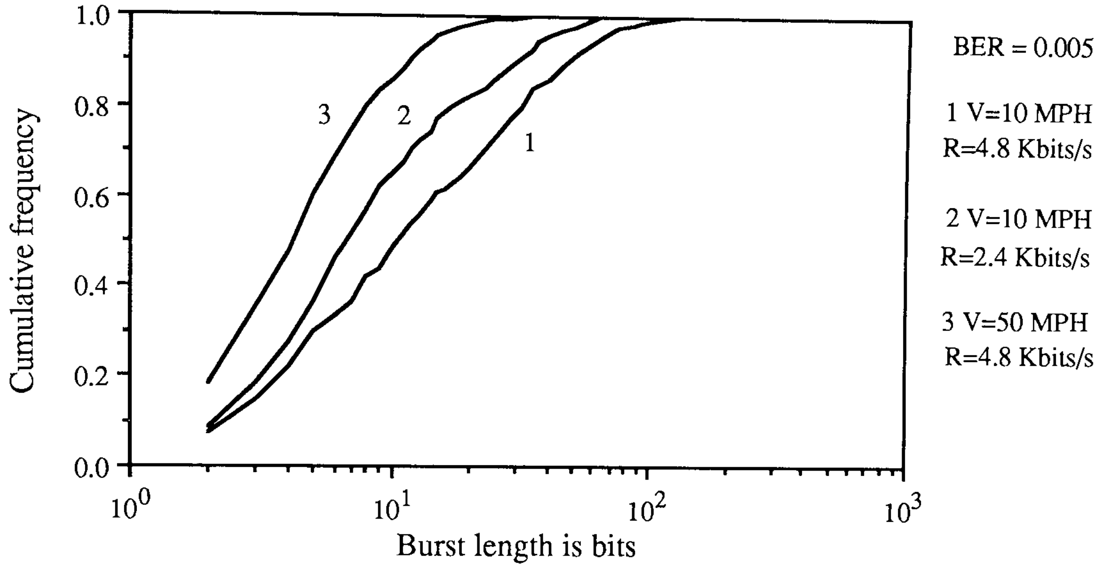


Fig. 4.12 Burst distributrion for a fading channel at SNR = 10 dB

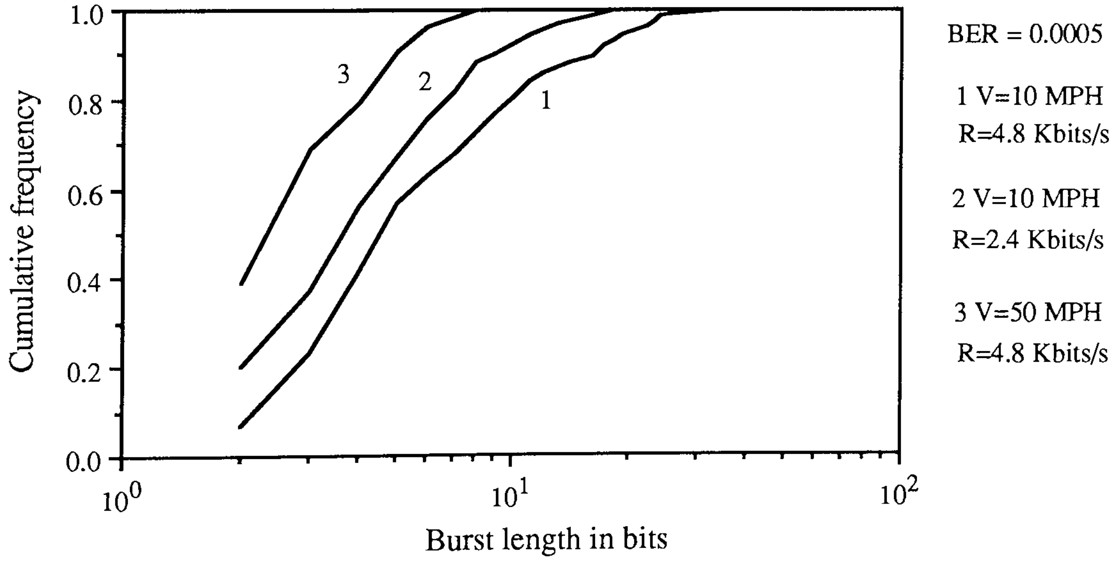


Fig. 4.13 Burst distribution for a fading channel at SNR = 20 dB

D) Block Error Statistics

This analysis examines the pattern distribution of errors in the error file by finding the number of errors in different block sizes. The information is presented as the probability P(≥m, n) of finding a given number of errors (m) or more in a block of size (n) bits as a function of the number of errors. This distribution is useful in choosing a suitable error control code because it gives the number of errors in a block that an error detecting or correcting code must deal with. To obtain the probability P(≥m, n), the stored data for an error file (900000 bits) is broken up into blocks of different sizes (e.g., blocks of size n = 7, 15, 31, 63 bits) and the P(≥m, n) for each block is calculated. The analysis is repeated for all blocks and the average value of the P(≥m, n) for each block size is obtained.

Fig. 4.14 gives the P(≥m, n) obtained from the error file 9, at a transmission rate of 2400 bits/s, a vehicle speed of 10 MPH, a SNR of 5 dB (BER = 0.017) and for different block sizes. The family of curves shows that the number of errors in a block is strongly related to the block size, with more errors occurring at larger block sizes.

Fig. 4.15 gives the P(≥m, n) for the same channel parameters but with higher vehicle speed of 50 MPH, error file 10. Comparison with Fig. 4.14 shows that the curves are notably steeper. This indicates that the probability of a small number of errors in a block is higher at high speed [60, 111]. This confirms the theoretical deduction that at high vehicle speeds the average fade rates increase and the average fade duration decreases.

Fig. 4.16 shows the P(≥m, n) for the same channel parameters as in Fig. 4.14 but with a higher transmission rate of 4800 bits/s, error file 11. In comparison with Fig.4.14, it can be seen that the probability P(≥m, n) to obtain m or more errors in a block of size n is slightly higher at higher transmission rates.

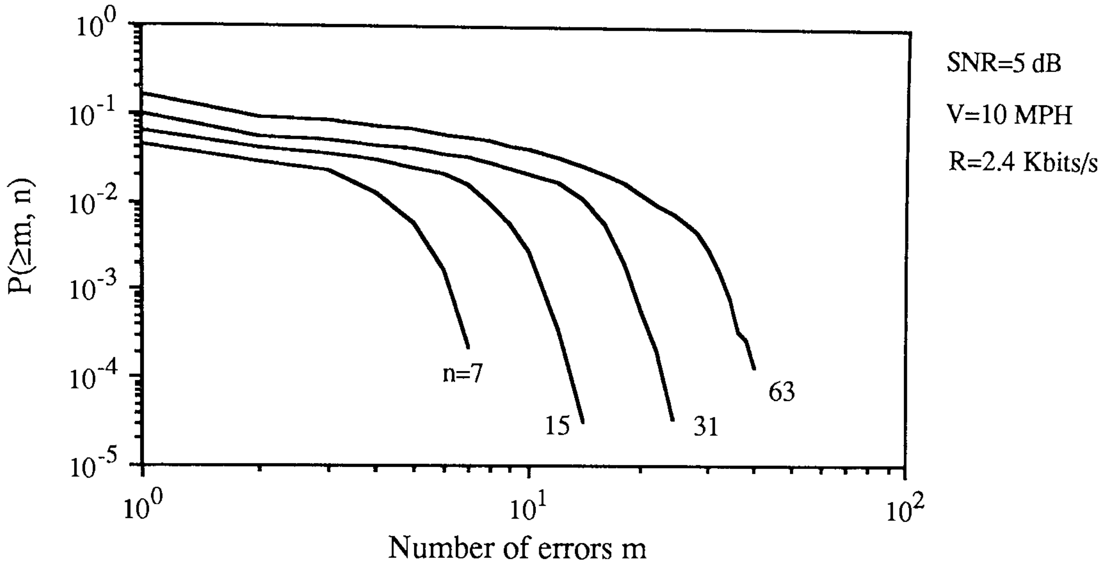


Fig. 4.14 P(≥m, n) for a fading channel (error file 9)

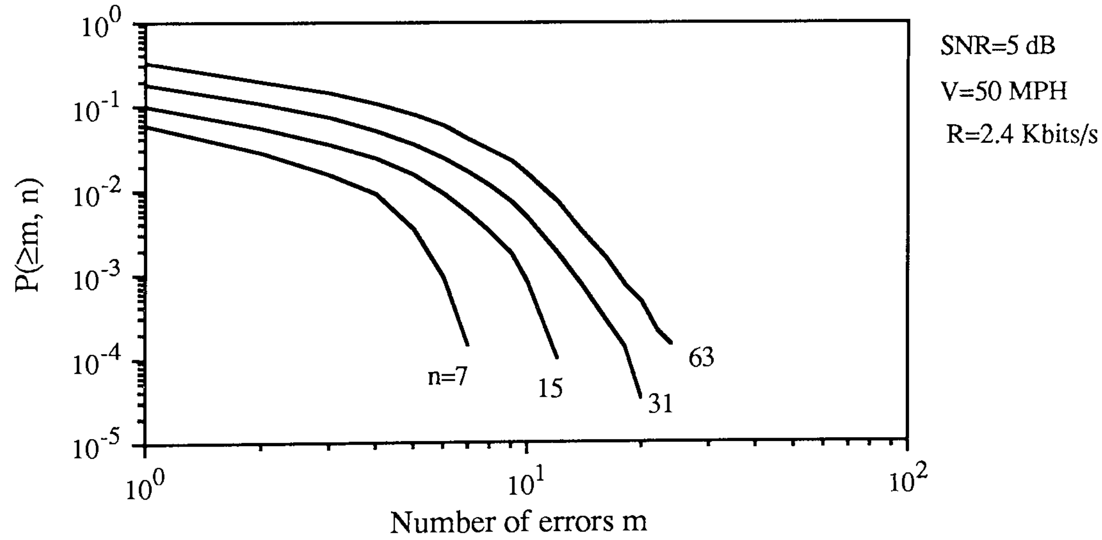


Fig. 4.15 P(≥m, n) for a fading channel (error file 10)

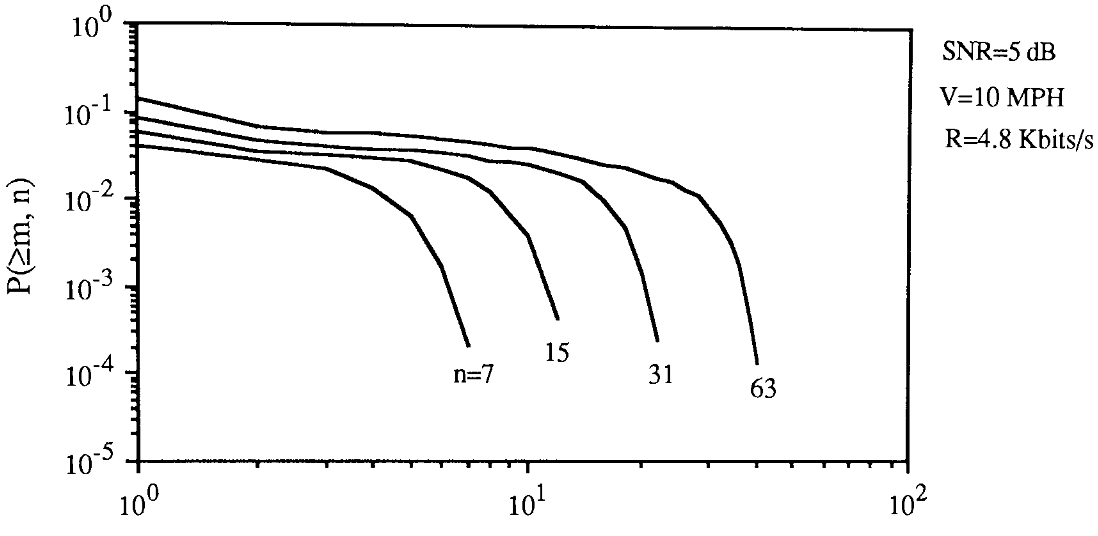


Fig. 4.16 P(≥m, n) for a fading channel (error file 11)

4.5 Summary

This chapter commenced with an introduction to the characteristics of the mobile radio channel. Based on many published studies, it was shown that the multipath fading phenomena causes the most serious disturbances to the quality of the transmitted signal. The mobile channel was represented by a multipath fading model based on the two-state Gilbert-Elliott Model. Computer simulation was carried out to generate digits in the fade and nonfade states and the digits were stored in an error file of size 900000 bits. A total of 12 error files were generated, in which about 12.8 million bits were used to represent a digital mobile channel error source under various channel conditions. The bit error statistics of the error files show that errors in mobile channels occur in burst patterns. The length and frequency of the error bursts vary considerably with various conditions of the channel, such as vehicle speed. The BER of the error files ranged from 0.017 at a SNR of 5 dB, 0.005 at SNR of 10 dB and 0.0005 at a SNR of 20 dB. The results obtained using the error files were compared with results conducted by field measurements and a good matching between the two sets of results were observed. The error files are thus a good representation of real error statistics for digital mobile radio channels and are used to evaluate the performance of the transmitted image data in the following chapters.

CHAPTER 5

TRANSMISSION OF IMAGE DATA TO MOBILE CHANNELS WITHOUT ERROR PROTECTION

5.1 Introduction

In chapters 3 and 4 a low bit-rate source encoding used to represent line diagram images for transmission over mobile channels and the modelling of the mobile radio channels were presented. This chapter deals with the effect of errors due to mobile transmission on the performance and the quality of the transmitted unprotected line diagram images. The method of assessing the performance of an image transmitted over a communication channel is usually by subjective assessment tests. The assessment has its basis in the visual observation of the transmitted image and the reproduced image at the receiver including the effect of transmission errors. In order to determine the subjective assessment, two line diagram images are considered as test images, the 4th floor plan of the north wing building at Aston University and the Aston University campus as shown in Figures 3.4 and 3.5.

Generally the quality of the reproduced image at the receiver is affected by the type or efficiency of the source coding used to generate the image and by the transmission errors. Intuition indicates that if the source coding scheme is optimum or efficient in a redundancy sense, then the information to be transmitted will be the most liable to transmission errors. Geometric coding is an efficient type of source coding used to represent line diagram images and it is expected therefore that both the high BERs and bursty nature of mobile transmission errors will seriously affect the performance and quality of the reproduced images. The key factors in mobile channels affecting the characteristics of the channel are vehicle speed, transmission rate and SNR. These will each have an effect on the quality of the transmitted line diagram images.

To obtain reliable transmission of line diagram image data over a mobile channel, a channel error protection scheme is therefore necessary to protect the transmitted image data. In order to determine the amount of error protection and the type of error protection protocol necessary to protect the geometric source codes, it is helpful to observe the subjective performance when no protection is provided. These test results could also indicate the mobile channel conditions required, such as the bit error-rate, if the test images are to be transmitted without error protection.

Before conducting the subjective tests it is useful to observe the effect of transmission errors on various bit positions of the opcode and parameter data of different graphical elements within the transmitted test image file. Errors are thus deliberately added to a particular bit position of an element and the effect is determined. In this way, information is obtained about the relative importance of each bit position in a graphical element. Based on this information, a receiver protocol is developed to process and reproduce the received test images corrupted with errors due to mobile transmission.

Further tests involve subjecting the line diagram test images to various mobile channel environment features (e.g., velocity of the mobile, SNR ratio and transmission rate, which affect on the type and rate of the transmission errors), to see how the image source encoding data stands up to mobile channel errors. Results and information obtained from subjective tests will indicate methods and types of channel error protection to be used to protect source image data so that it can tolerate the diverse mobile environments.

5.2 Effect of Errors on the Unprotected Graphical Elements

It has been shown how the graphical elements Line, Marker, Polygon, Rectangle and Text can be used to represent line diagram images. For the case of a transmission channel without errors, a computer program was adopted at the receiver to read the data of graphical elements within the transmitted image file, process the data and reproduce the image, see chapter 3. Transmission errors, however, affect the unprotected graphical elements in such a way that it changes the type of the codes within a graphical element. For example, within a graphical line element, errors may change the POLYLINE opcode

(0100000) to the POLYMARKER opcode (0100010). Errors can also change the format of the opcode to a parameter code or vice versa. It is also possible that errors may affect the bitstream of the parameter data used to locate the position of drawing elements. In the following sections of this chapter a protocol is developed to deal with various types of erroneous graphical elements. The minimum error handling which should be performed by the receiver protocol is also given.

In general, errors affect or change the transmitted graphical elements in two ways:
1) Errors change the construction of a graphical element in such away that it differs from the normal graphical element construction known by the receiver protocol. In this case the received element is detected by the receiver protocol as an erroneous element. If the receiver protocol cannot interpret the erroneous element, then the protocol action is to delete the erroneous element and the subjective effect of such an error is that the shape represented by the erroneous element is missing from the original shape.
2) Errors change the construction of a transmitted element such that the changed element cannot be detected by the receiver as an erroneous element. In such a case, the receiver processes the erroneous element codes as correct codes and the subjective effect of such errors is that the displayed image is corrupted in some way.

In the following, we first consider the effect of errors on the unprotected graphical geometric elements, such as Line, Marker, Polygon, Rectangle, which are similar in construction and used in this work to represent geometric shapes in the line diagram test images. Then we find the effect of errors on the unprotected graphical Text element which is used to represent string text data in the line diagram images. When considering the effect of errors in a bitstream of a certain code byte within a graphical element, the other code bytes are assumed error-free unless stated otherwise.

5.2.1 Effect of Errors on the Unprotected Graphical Geometric Elements

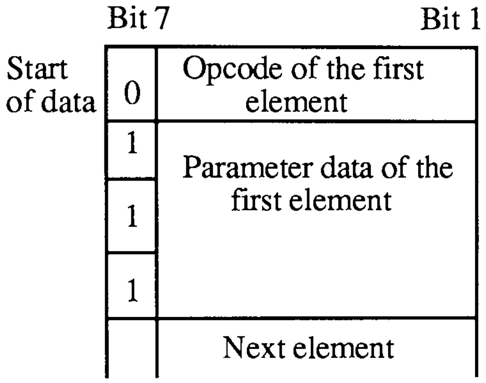
For the graphical geometric elements Line, Marker, Polygon, Rectangle, each element starts by an opcode followed by a certain number of parameter data bytes and ended by a next opcode or a specially defined code by the receiver protocol. The number of parameter code bytes in each element varies according to the drawing details of the element. In the following, the effect of errors deliberately introduced into various bit positions within a graphical element is considered.

A- Errors in the Opcode of a Graphical Geometric Element

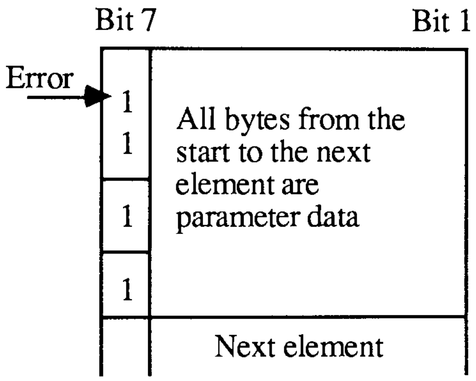
An opcode is a code of 7-bits length and is the first (header) byte of any graphical element. An opcode represents a command to the receiver to plot a specific drawing. The parameter data following the opcode represents the coordinates of a point or points at which the opcode is drawn. It is clear that the opcode is an important item of information within any graphical element and that an error in the bitstream of the opcode would disturb the shape of the transmitted image from a subjective point of view. Results obtained are as follows.

A1- Errors in bit 7 and any other bits of the opcode

An opcode byte is recognized from a parameter data byte format by the flag bit 7 which is equal to 0 in the opcode byte and 1 in a parameter data byte. An error in bit 7 of the opcode results in changing the opcode format to parameter data. For example, the opcode POLYLINE 0100000 changes to 1100000 which means a parameter data code. If errors occur in bit 7 and any other bitstream of the opcode (i.e., bit 6 ..... bit 1), the result is also a change of the opcode format to a parameter data code. Such errors result in the opcode being processed by the receiver as a parameter byte belonging to the preceding element. If the flag bit 7 of the following parameter bytes within the element are without errors, then the receiver processes them also as parameter data belonging to the preceding element. In the case where the erroneous opcode belongs to the first starting element of the transmitted data, then the receiver protocol ignores all codes from the start to the next opcode, as illustrated below.

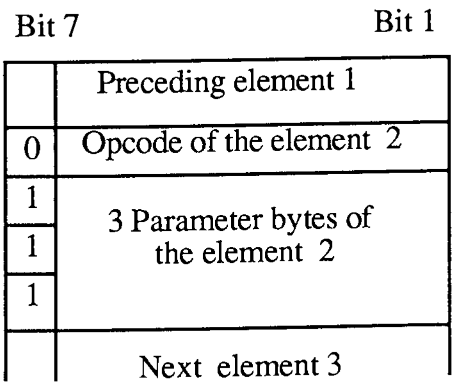


Data of the start ing drawing element

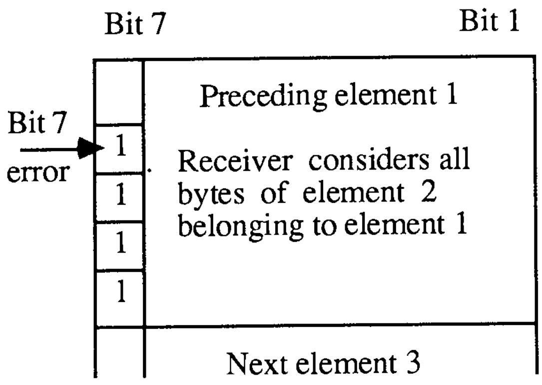


Error in the bit 7 of the opcode of the first element

The subjective effect of such an error is the missing of the drawing shape specified by the starting element in the reproduced image. When the erroneous opcode of an element is located between a sequence of transmitted elements, then the receiver considers the erroneous opcode of the element 2 which has changed to a parameter data and the following parameters data of the element 2 as extension parameters data of the preceding element 1, as shown below.



Sequence of drawing elements within the transmitted data



Error in bit 7 of the opcode of the element 2

Adding new parameters data to the preceding element would cause the following effects. If the total number of the code bytes of the erroneous and the preceding elements are accepted for processing by the receiver protocol (e.g., in the case of the marker element the maximum allowed number is 19 code bytes which is required to draw six markers), then the subjective effect of such an error is that the receiver draws the shape of the element 1 and then draws an erroneous shape added to the end of the shape of the element 1. The erroneous shape is specified according to the added erroneous opcode of the element 2 which has changed to parameter data and the parameter data of the element 2. If the total number of code bytes of the erroneous and the preceding elements are not accepted by the receiver protocol, then the receiver deletes the data, and the subjective effect is missing the shapes specified by the element 1 and the erroneous element from the reproduced image.

A2- Bit 7 is correct, errors in bits 6 or 5 and any other bits of the opcode

It has been mentioned that single-byte opcodes will be used in this work. These opcodes are coded from column 2 of the code chart and hence all opcodes should assign b7=0, b6=1, b5=0. Errors in bits 5 or 6 result in an unknown opcode format at the receiver and such an error is therefore detectable. The receiver protocol ignores the unknown opcode and the following parameter data up to the next opcode. The subjective effect of such errors is the missing of the drawing shape specified by the unknown opcode and the following parameter data up to the next opcode.

A3- Bits 7-5 are correct, errors in any bits 4-1 of the opcode

This results in two different conditions.

1. Errors change the type of the opcode to another known type.

For example, if bit 2 of the opcode of a line element is affected by an error, then the POLYLINE opcode format 0100000 is changed to the new POLYMARKER opcode format 0100010. The protocol processes the changed erroneous marker element as follows:

If the number of the parameter code bytes following the POLYMARKER opcode is accepted, then the protocol cannot detect the erroneous marker element. The subjective effect of this error is that one or more markers will be located in the reproduced image at positions specified by the parameter data of the original line element.

If the number of the parameter code bytes following the POLYMARKER opcode is not accepted by the receiver, then the protocol detects the erroneous marker element. The subjective effect of this error is missing the shape of the line element.

2. Errors change the type of the opcode to a type unknown (e.g., 0101111 code).

This error can be detected, the receiver protocol deletes this opcode and the following parameters data up to the next opcode. This error will be manifested at the receiver by a missing drawing shape defined by the element with the erroneous opcode.

Generally, it can be said that an error in any bits of the opcode of an element results in disturbing effects to the reproduced image at the receiver which range from;

1) Missing a geometric shape from the reproduced image which is defined by the graphical element with the erroneous opcode.

2) The original geometric shape defined by an opcode changes to another shape defined by the erroneous opcode (e.g., the line shape changes to a marker shape).

3) Missing from the reproduced image a geometric shape which is defined by the graphical element with the erroneous opcode and also disturbing the geometric shape defined by the preceding graphical element.

4) Missing from the reproduced image both geometric shapes which are defined by the element with the erroneous opcode and the preceding element.

B- Errors in Parameter Data of a Graphical Geometric Element

Code bytes following opcodes are known as parameter data. In Fig. 5.1 six code bytes are used within the marker element 2 as parameter data to locate the coordinates of two markers. The first three bytes 2 to 4 are used to locate the position of the first marker and bytes 5 to 7 are used to locate the position of the second marker. Bits X1, Y1, C1 and D1 are the most significant bits of the first and the second marker and bits X9, Y9, C9 and D9 are the least significant bits. Errors are introduced into the six byte parameter data of the marker element 2 as follows.

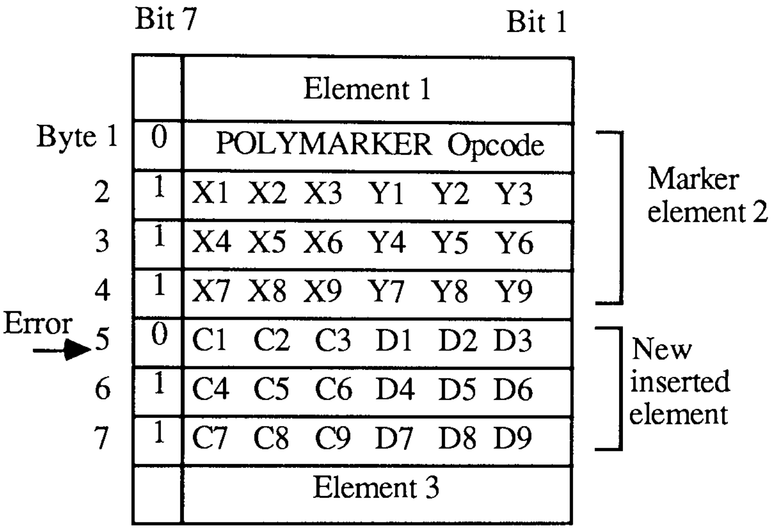
Byte	Bit 7	Bit 1	
		Element 1	
1	0	POLYMARKER Opcode	Marker element 2
2	1	X1 X2 X3 Y1 Y2 Y3	
3	1	X4 X5 X6 Y4 Y5 Y6	
4	1	X7 X8 X9 Y7 Y8 Y9	
5	1	C1 C2 C3 D1 D2 D3	
6	1	C4 C5 C6 D4 D5 D6	
7	1	C7 C8 C9 D7 D8 D9	
		Element 3	

Fig. 5.1 Sample of drawing elements within the transmitted image file

B1- Error in bit 7 only of any parameter data bytes

Bit 7 of any parameter data byte is the flag bit which is equal to 1. This bit distinguishes a parameter code byte from an opcode byte. If an error occurs in bit 7 and the pattern of bits 1 to 6 within the code byte is similar to an opcode, then the receiver will consider the code byte as an opcode. A simple example shows how this takes place. Consider the sequence of code bytes within the marker element 2 as shown in Fig. 5.1 If an error occurs in bit 7 of the code byte 5, then the sequence of code bytes within the marker element 2 becomes as in Fig. 5.2. Hence the error causes insertion of a new opcode within the code bytes of element 2. The new code bytes sequence is therefore decoded by the receiver protocol as two elements. The first element consists of the original POLYMARKER opcode followed by three parameter code bytes 2-4. The new inserted opcode starts at the code byte 5 followed by two parameter code bytes 6 and 7.

The subjective effect of such an error is that the original shape which consisted of two markers is now changed to a drawing of the first marker. The inserted opcode then specifies the type of the new inserted geometric shape to be drawn. If the pattern of the new inserted opcode is an unknown pattern, then the protocol deletes the opcode followed by the parameter code byte up to the next opcode. However, if the pattern of the new inserted opcode and the number of the parameter data following the new inserted opcode is accepted by the receiver protocol, then the receiver draws a new drawing shape in the original image. The shape of the new drawing element depends on the type of the opcode and the following parameter data. In Fig. 5.2 the new inserted element is deleted by the receiver protocol because the number of the parameter data is less than 3, which is the minimum accepted value by the receiver.



	Bit 7	Bit 1	
		Element 1	
Byte 1	0	POLYMARKER Opcode	Marker element 2
2	1	X1 X2 X3 Y1 Y2 Y3	
3	1	X4 X5 X6 Y4 Y5 Y6	
4	1	X7 X8 X9 Y7 Y8 Y9	
Error → 5	0	C1 C2 C3 D1 D2 D3	New inserted element
6	1	C4 C5 C6 D4 D5 D6	
7	1	C7 C8 C9 D7 D8 D9	
		Element 3	

Fig.5.2 Sample of drawing elements with an error causing a new inserted element

B2- Bit 7 is correct, errors in any other bits of the parameter data

It has been mentioned that to locate a marker within a line diagram image requires 3 bytes of parameter data assuming a resolution of 512x512 pixels or positions. In Fig. 5.1 above, bit 6 (X1) and bit 3 (Y1) of the first parameter code byte represent the most significant bits of the X,Y coordinates of the first marker. Errors in these bits change the coordinates value of the first marker by (256 / 512), where the maximum coordinate value is 1. For example, assume the coordinates value of the first marker is at (X= 0, Y= 256/512 = 0.5) as shown below:

X1	X2	X3	X4	X5	X6	X7	X8	X9	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

If an error occurs in the most significant bit X1, then the coordinates of the first marker is changed to (X=256 / 512 = 0.5, Y=0.5) as shown below:

X1	X2	X3	X4	X5	X6	X7	X8	X9	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

The subjective effect of such an error is that the value of the coordinates where the marker to be located is shifted from (X=0, Y=0.5) to (X=0.5, Y=0.5). This change or shift represents half the maximum shift in the coordinate values.

- Errors in bit 5 or bit 2 of the first parameter code byte

Bit 5 (X2) and bit 2 (Y2) of the first byte represent the first bits following the most significant bits. The subjective effect of this error is similar to the case B2 above but the error value or change in the coordinates is less and equals 128 / 512.

- Errors in bit 4 or bit 1 of the first parameter code byte

The subjective effect is similar to B2 but the error value is 64 / 512.

- Errors in bit 6 or bit 3 of the second parameter code byte

The subjective effect is similar to B2 but the error value is 32 / 512.

- Errors in bit 5 or bit 2 of the second parameter code byte

The subjective effect is similar to B2 but the error value is 16 / 512.

- Errors in bit 4 or bit 1 of the second parameter code byte

The subjective effect is similar to B2 but the error value is 8 / 512.

- Errors in bit 6 or bit 3 of the third parameter code byte

The subjective effect is similar to B2 but the error value is 4 / 512.

- Errors in bit 5 or bit 2 of the third parameter code byte

The subjective effect is similar to B2 but the error value is 2 / 512.

- Errors in bit 4 or bit 1 of the third parameter code byte

The subjective effect is similar to B2 but the error value is 1 / 512.

It can be observed that an error in the most significant bits X1 or Y1 results in a large shift or error in the coordinates value of a point. Errors in other bits following the most significant bits produce a similar effect but the change or error is less, depending on the bit position within the code bytes.

Errors in parameter code bytes 5, 6, 7

These bytes represent the coordinates value of the second marker. The effect of errors in these parameter bytes are similar to those specified for the first marker described above.

It can be said, therefore, that an error in any bit within a parameter code byte results in disturbing effects to the reproduced image at the receiver which range from:

1) Missing part of the drawing element shape from the reproduced image. For example, errors change a line consisting of 4 location points to a line with 2 points. The missed part may be decoded as a new inserted drawing element shape to the reproduced image.

2) Errors or shift in the coordinate values of the drawing shape, where the amount of the shift or change depends on the position of the erroneous bit within the parameter data.

5.2.2 Effect of Errors on the Unprotected Graphical Text Element

The format of a graphical text element is slightly different from the graphical geometric elements mentioned previously. When the protocol receives the TEXT opcode then it considers that a text element has started. To obtain the effect of channel errors on the unprotected graphical text element it is helpful to give the format of the element as an example. For this purpose, the text element used to draw the word FLOOR as shown in Fig. 3.3 in chapter 3 is considered. The effect of errors in each code byte within the element is given as follows.

C- Errors in the Opcode of the Graphical Text Element

The TEXT opcode is the first code of the text element. It is a command instructing the receiver that a text element has started. Results of subjecting the opcode bits to errors are obtained as follows:

C1- Errors in bit 7 and any other bits of the TEXT opcode

Errors introduced in the bit 7 and any other bits of the opcode change the opcode format to a parameter data as shown below in Fig. 5.3. The erroneous opcode will now be shown as parameter data and the following 4 code bytes (3 bytes parameter data + 1 byte flag code) are now considered as parameter data belonging to the preceding element. To end the content of the preceding element the receiver continues reading next data looking for an opcode, SI or SO code. The receiver detects the next code as SI code which is known as a special code belonging to a text element. The receiver protocol assumes that the SI code is a part of an erroneous text element, since the format of the TEXT opcode has changed due to errors to a parameter data. To confirm the occurrence of the erroneous text element and the length (number of code bytes) of the element, the receiver should obtain the SO code which is a special code format indicating the end of the text element.

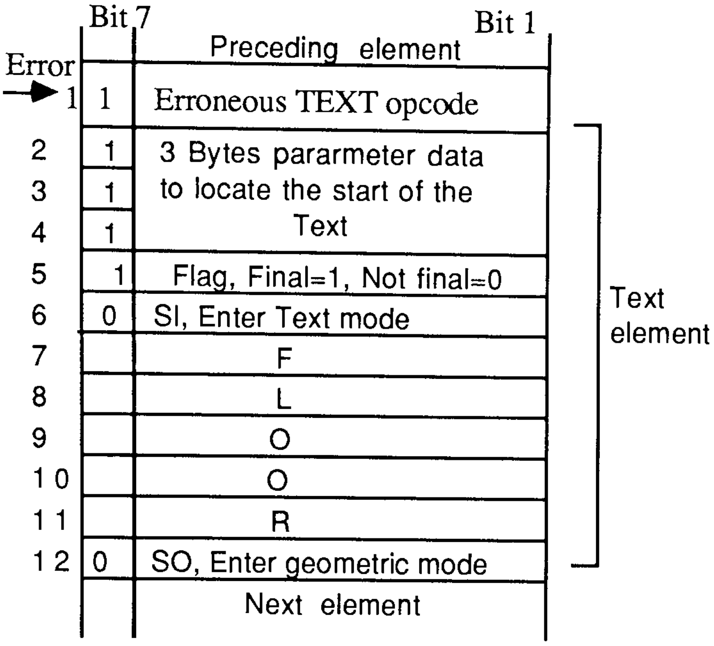


Fig.5.3 Erroneous opcode in a Text element.

If the SO code is obtained within a certain number of code bytes after the SI code (e.g., 20 code bytes, where each code represents a string to be produced), then the protocol assumes that a text element is received, where both the SI and SO control codes are considered as part of the text element. The number of code bytes between SI and SO codes represents the number of strings within the used text. The protocol detects that the obtained text element is in error, since the TEXT opcode, which should precede the SI code by five code bytes, is not obtained due to the errors. It is also possible that errors, which often occur in burst form, might have affected other code bytes within the text element. As a result, the action of the receiver protocol is to delete the erroneous text element from the image file data. The subjective effect of such a case is to delete the word FLOOR from the reproduced image.

If the SO code is not obtained due to errors, the protocol assumes that the received SI code is in error and is not a part of a text element. The protocol processes the preceding element up to the erroneous SI code, deletes the erroneous SI code and starts processing the next code bytes following the erroneous code SI. The subjective effect of such a case is to introduce errors in the preceding element and the text element is missing from the reproduced image.

C2- Bit 7 is correct, errors in bits 6 or 5 and any other bits of the opcode

Errors in bits 5 or 6 of an opcode results in an opcode format unknown to the receiver and such an error can be detected. The result of such an error is that the receiver ignores the unknown opcode and the following parameter data until it receives an opcode, SI or SO code. When the SI code is received, then it is assumed to be a part of an erroneous text element. The receiver processes the next codes as in the case C1 above.

C3- Bits 7-5 are correct, errors in any bits 4-1 of the opcode

This results in two different situations.

1. Errors change the TEXT opcode to other known opcodes, for example, if an error affects bit 1 of the TEXT opcode (0100011), then the opcode is changed to the POLYMARKER (0100010). The receiver processes the next data as parameter data of the marker element. When the SI code is received after the 3 bytes parameter data + 1 byte flag code, then it is considered as a part of an erroneous text element. The receiver processes the next codes as in the case C1 above.
2. Errors change the TEXT opcode to a type unknown to the receiver. This case is similar to the case C2 above.

In general, it can be said that an error in any position of the bitstream of the TEXT opcode produces the following:

- change of the opcode format to a parameter data
- change of the opcode to another known opcode
- change of the opcode to an unknown opcode

If we assume that the other code bytes of the text element are without errors, then the receiver protocol can detect all the above errors in the opcode. However, due to the bursty nature of the errors, the protocol assumes that other undetected errors might have occurred in the text element and considers the element as an erroneous text element. This means that the protocol ignores all the code bytes within the erroneous text element. The subjective effect of such errors is that the text element which contains the word FLOOR is missing from the image.

D- Errors in the Code Bytes Following the TEXT Opcode

In this case we assume that the TEXT opcode is received without errors. Errors are introduced in the bitstream of the code bytes following the TEXT opcode as follows.

D1- Errors in the parameter data of the text element

Parameter data of three bytes are used to locate the position of the text FLOOR or any other text positions in the displayed image. Errors can affect the bitstream of the parameter data as follows:

1. Errors only in the flag bit 7 of any code bytes of the parameter data

Such an error changes the format of the parameter data to an opcode. This results in the production of two or more opcodes within a sequence of four code bytes. The protocol considers that errors have occurred in the TEXT opcode and the following 3 bytes of parameter data. The protocol deletes the four code bytes and starts processing the next data. The next code is the flag code followed by the SI code. When the SI code is received, the next data is processed according to the case C1 above.

2. Bit 7 is correct, errors in any other bits within the parameter code bytes

Such errors change or shift the position of the text and cannot be detected. The amount of change depends on the position of the erroneous bits. For example, the effect of errors in the most significant bits of the X,Y coordinates is more serious than the lowest significant bits. More details are given in section 5.2.1 (B2).

D2- Errors only in the flag code byte of the text element

The flag code byte is used to instruct the receiver if the text to be drawn is final or not. If the text is final the value is 1 (1000001), if not the value is 0 (1000000). Error effects in the bitstream of the flag code are as follows.

1. Error only in bit 7 of the flag code

The receiver detects that the flag code in error. The protocol assumes that undetected errors might have occurred in other codes within the text element. Therefore the text opcode + 3 parameter codes + the erroneous flag code are ignored. When the next code SI is received, the next data is processed as in the case C1 above.

2. Errors in bits 2-6 of the flag code

The same effect is obtained as in 1 above.

3. Error only in bit 1 of the flag code

This affects the number of the strings to be processed. For example, if the value of the bit is 0, which means that more than one string should be processed, then when it is affected by an error the value is changed to 1. The erroneous value 1 means that a text of only one string is allowed and therefore the receiver processes only one string of the text. If the value due to an error is changed from 1 to 0, then the receiver considers that more than one string should be drawn. Thus the receiver draws a series of strings until a next opcode, SI or SO code is obtained. Such an error cannot be detected by the protocol.

D3- Errors in the SI code

This is a special control code used to instruct the receiver to change from a geometric mode to a text mode, it is therefore an important code. An error in any bit within the SI code is detected assuming the other preceding code bytes of the text element are without errors. When an error is detected, the protocol assumes that errors might have occurred in other codes within the text element. The protocol deletes the text opcode + 3 parameter data + the flag code + the erroneous SI code and starts processing the next data.

D4- Errors in the string data

In a text element, string data is represented by code bytes which start after the SI code up to the SO code. Two types of text are allowed, the first is a text with only one string, e.g., a string used to locate a certain number in the image. The second type is a text with more than one string, e.g., the text FLOOR. In the second type we assume there is a maximum allowed number of 20 strings within the drawn text. The receiver distinguishes the two types according to the flag value. In the following the effect of errors on both types are considered.

1) If the flag = 1, one string is allowed. Errors can affect the string as follows:

a) Change the type of the string. For example, in the UK 7-bit code table, the code 1100010 represents the letter b. If errors change the code to 1100011 format then, from the UK 7-bit code chart, the receiver processes the code as the letter c.

b) If errors change the format of a string to a code similar to that located within columns 0 or 1, then the protocol detects that the string is in error. The receiver ignores the erroneous string and, as a result, the string is missed from the image.

2) If the flag = 0, more than one string is allowed. Errors can affect the strings as follows:

a) Change the type of the strings within the columns 2 to 7 of the UK 7- bit code chart. This is similar to case (a) above.

b) Change the type of a string format similar to that in columns 0 and 1. In this case, if the changed code is different from the SO code, then the format is unknown to the receiver and is deleted. If the errors change a string code to the SO format, then the protocol assumes this SO code to be the end of the text element. As a result, the strings within the text element will be processed up to the SO code, since the SO code indicates the end of the text element. For example, if errors have changed the code byte of the string R of the word FLOOR to the SO code, then the receiver processes the strings FLOO only. The subjective test result is that the word FLOOR is now shown as FLOO only, and the last string R is missed.

D5- Errors in the SO code

This is a special code byte used to indicate the end of the text element. Errors in the SO code results in changing the position of the text end. For example, the position of the erroneous SO code could add or delete several strings to the original text. In the case of a text element without error, the SO code is used to instruct to receiver to change from the text mode to the geometric mode.

5.2.3 Receiver Protocol to Process the Unprotected Image Data Subjected to Mobile Transmission Errors

In the previous section we determined the effect of errors on various bitstream positions of code bytes of the graphics elements. It was shown that errors change the construction of code bytes within graphical elements. When an erroneous element is detected, the receiver may delete the erroneous element, e.g., in the case where the erroneous element cannot be interpreted or processed by the receiver protocol, and hence the shape represented by the graphical element is missed from the image. Other errors produce various effects in the graphical elements such as errors in coordinate values of a drawing element, changing the type of a drawing element, errors in text format and so on.

From this information, a receiver protocol was developed which is able to process and deal with all types of graphical element data in the received image file subjected to simulated mobile channel errors. The protocol was implemented by computer simulation. In the following, a summary of steps carried out by the receiver protocol to process the received image file data is given.

1- Store the received image file data to be ready for processing.

2- Read the stored image data from the beginning of the file in a form of code bytes, where each code byte consists of 7 bits.

3- The protocol starts from the beginning of the received image file and searches for the first opcode of a graphical element to initiate a start. If a known opcode is obtained, then it means the first graphical element has started. The code bytes following the opcode represent the parameter data of the first graphical element.

4- The end of the first element is located when receiving the next opcode, SI or SO code.

5- If an unknown opcode or a parameter code has started from the beginning of the data, then it means that errors have occurred. The protocol deletes the starting code byte and the following codes until it obtains a known opcode.

6- When the first element is obtained, the protocol starts to test if the number of code bytes within the element agrees with the allowed minimum and maximum number for the specific element. If the number of code bytes is accepted, then the element is stored to be processed later. If the number is different, then the code bytes of the element are ignored. After testing the element, the protocol starts dealing with the next data code bytes.

7- The protocol continues reading and testing the next code bytes up to the end of the image file.

8- At the end of the image file data, the protocol starts to process and reproduce the drawing shapes of the tested graphical elements. For this stage, a computer program has been written using the GKS graphic system, which is based on geometric drawing elements as described in chapter 3. The GKS program reads the image file data subjected to transmission errors, processes the image file data according to the above protocol and then reproduces the image shape in the form of computer plots ready for subjective assessment tests.

5.3 Subjective Performance Tests of the Unprotected Image File Data Subjected to Mobile Transmission Errors

Having determined the effect of errors on various bit positions of graphical elements, the line diagram test images composed of various graphical elements were subjected to computer simulated mobile channel transmission errors. The effects on the unprotected test images were then observed subjectively. Two line diagram test images were considered, the 4th floor plan of the north-wing building at Aston University and Aston University campus map as shown in Fig. 3. 4 and 3.5 in chapter 3. The simulated mobile transmission errors were obtained from error files for various channel environments which affect the error-rate and the type of error, e.g., SNR, velocity of the mobile and transmission rate. The process of error generation on the transmitted test image data was carried out as a modulo-2 summation of the transmitted image bit sequence and a randomly selected sequence from the required error file.

A number of transmission tests were carried out for each test image and error file. In each test, a random position within the error file was selected and the image file data was added to the content of the error file from the randomly selected position of the error file up to the end of the image data. The result was the transmitted image data corrupted with mobile channel errors. At the receiver, the protocol mentioned previously interpreted and processed the received image data to reproduce the image shape. The reproduced images, which may contain erroneous drawing elements according to the mobile channel conditions, were recorded in the form of computer plots ready for subjective assessment tests.

The CCIR recommendation 500 [73], used for the subjective assessment tests of the quality of the television pictures [71, 72] , can also be used for subjective assessment of other types of pictures. International standardization test procedures for evaluating the quality of compressed still frame grayscale or colour pictures have recently been described

[75, 76]. The quality of these images were evaluated using a modification of the CCIR Rec. 500 television quality evaluation procedures. Subjective assessment tests based on the CCIR Rec.500 have been also adopted for the evaluation of facsimile images transmitted through mobile terminals [51, 52]. The subjective assessment tests of the quality of the line diagram images in this work are therefore conducted based on the CCIR Rec.500. The five-point scales as shown in Table 5.1 are used as a quality scale or an impairment scale in the CCIR Rec. 500.

Table 5.1 CCIR Rec. 500 five-point grade scales

Quality	Impairment
5 Excellent 4 Good 3 Fair 2 Poor 1 Bad	5 Imperceptible 4 Perceptible but not annoying 3 Slightly annoying 2 Annoying 1 Very annoying

Based on the CCIR Rec. 500, we use two appropriate grading scales for the subjective assessment of the line diagram images, known as quality and usefulness scales as shown in Table 5.2.

Table 5.2 Five-point grade scales for line diagram images based on CCIR Rec. 500

Quality	Usefulness
The effect of errors on the line diagram image: 5 Imperceptible 4 Perceptible but not annoying 3 Slightly annoying 2 Annoying 1 Very annoying	The effect of errors on the line diagram image: 5 Not significant 4 Significant but not misleading 3 Slightly misleading 2 Misleading 1 Severely misleading

The reason for using the two grading scales is as follows. Because the two line diagram test images each consist of many separate drawing elements, certain errors within an image might not be perceptible from the quality point of view, but could nevertheless be misleading from the usefulness point of view. An example to demonstrate the advantages of using two types of grading scales is therefore given. Consider the transmission of test image 2, as shown in Fig.3.5, over the mobile channel. In a certain transmission test, channel errors caused a missing geometric element in the test image 2. The missed element was a small rectangle shape and for explanation purposes the location of the missed element in the reproduced test image 2 is marked (X) in Fig. 5.4. It is to be expected that missing a small size geometric element from a test image that consists of many geometric elements might not be perceptible from the quality point of view. Nevertheless, the missing element might be considered as somewhat misleading from the usefulness point of view. We therefore carried out two types of subjective tests for each test image. The first test relates to the quality and the second relates to the usefulness of the images when corrupted by errors.

In the quality evaluation test, the observer examined the master test images 1 and 2 as shown in Figures 3.4 and 3.5 for a certain time (each about 1 minute) and then examined a number of transmitted test images subjected to channel errors and graded them according to the quality grading scale shown in Table 2. In the usefulness evaluation test the errors in the received test images were marked and the observer compared the significance of the errors on the received test images with the master test image and graded them according to the usefulness grading scale shown in Table 2. In both the quality and usefulness evaluation tests, an image under test was shown for about 15 seconds, then followed by a brief time for marking scores before the next test image [113]. An average of about 25 test images were assessed at each session. This made a scoring session for each case last for no longer than about 10 minutes. The number of observers used to conduct the subjective assessment tests was 15, selected randomly from the University population.

Results

To determine the effect of the mobile channel on the subjective quality of the transmitted image data, different channel parameters were varied such as SNR (20 dB and 10 dB), transmission rate (2400 bits/s, 4800 bits/s), vehicle speed (low vehicle speed at 10 MPH and high vehicle speed at 50 MPH). Error files 1 to 8 were used to represent the above channel conditions, where each error file represents the channel as a real error source with certain specific parameters. For values of SNR 20 dB (error files 1-4) and SNR 10 dB (error files 5-8), the corresponding average BERs are about $5x10^{-4}$ and $5x10^{-3}$ respectively, see chapter 4. In this chapter, the effect of error files 9-12, which represent the channel at a lower value of SNR 5 dB (BER about $1.7x10^{-2}$), are not considered. This is because at such high values of BER it is expected that the performance of the transmitted unprotected test images would degrade severely. Moreover, the results of the error files 1-8 for higher values of SNRs would indicate if it is possible to adopt lower values of SNR.

Results in the form of Tables, bar charts and Figures in the form of photographs representing the effect of transmission errors on the received test images are presented [105]. Tables 5.3 to 5.10 show the results of the quality and usefulness analysis of the subjective performance tests for the test images 1 and 2 transmitted over a mobile channel, for various mobile channel parameters. In each Table, the results are represented as a percentage of the total number of test images of a given quality and usefulness grade on the five-point grade scale. The results in the Tables 5.3 to 5.10 are divided into groups. This makes it possible to show the effect of each mobile parameter on the subjective performance results. Tables 5.3 and 5.4 show the survey results of the performance analysis for a mobile channel of SNR 20 dB, transmission rate 2400 bits/s and two vehicle speeds (low speed of 10 MPH and high speed of 50 MPH). Tables 5.5 and 5.6 show the survey results when the transmission rate is increased to 4800 bits/s. In Tables

5.7 and 5.8 the survey results are shown for a lower value of SNR 10 dB, transmission rate 2400 bits/s and for two vehicle speeds (10 MPH and 50 MPH). Tables 5.9 and 5.10 show the results at SNR 10 dB, transmission rate 4800 bits/s and for two vehicle speeds (10 MPH and 50 MPH).

From the subjective performance results, a useful measure known as the average value of the usefulness or quality grade of the test image is obtained as follows:

Average grade value = (Number of images of grade 5 X 5 + ...+ Number of images of grade 1 X 1) / Total number of test images.

The average quality and usefulness grades for images 1 and 2 are shown in Tables 5.3 to 5.10. To show the results in more detail the average quality and usefulness grades for test images 1 and 2 are also represented in the form of bar charts versus error files 1 to 8 as shown in Figure 5.5.

From the subjective performance tests, the total number of the observed erroneous shapes in the test images 1 and 2 are counted. From this figure the average number of erroneous shapes in each test image is calculated and is given by:

Average number of erroneous shapes in the test image = Total number of the observed erroneous shapes / Total number of the test image shapes.

Table 5.11 shows the results of the average number of erroneous shapes in the test images 1 and 2 for various mobile channel parameters.
Several diagrams in the form of computer plots are given which represent the subjective effect of mobile channel errors on the transmitted test images 1 and 2. For explanation and to show the effect of the errors, the positions of erroneous elements are indicated by the symbol (x) within the test images.

Discussion of Results

The effect of various factors on the results of the subjective performance tests are discussed as follows.

A. The Effect of Image File Size

From Tables 5.3 to 5.11 it will be seen that the results of the subjective performance tests for the test image 1 are better than for the test image 2. This is because the size of the file for the test image 1 (3507 bits) is smaller than for the test image 2 (7595 bits) and therefore the average number of errors which occur due to the transmission channel is lower in the test image 1, which results in better subjective performance. For example, at SNR 20 dB, transmission rate 2400 bits/s and vehicle speed 50 MPH (error file2) the average number of erroneous shapes obtained in the test image 1 is 1.26, while in the test image 2 the average number is 2.84 (Table 5.11). For the same channel parameters the average quality grades for the test images 1 and 2 are 3.96 and 3.4 (Table 5.4). This shows that the size of the image file has an effect on the subjective performance results.

In good mobile transmission conditions, such as at SNR of 20 dB and a low vehicle speed of 10 MPH, acceptable subjective performance test results were obtained for both test images 1 and 2 (Table 5.3 and 5.5). Under such conditions, the effect of transmission errors on the test images 1 and 2 was, on average, perceptible but not annoying from the quality point of view, and significant but not misleading from the usefulness point of view. Usually, the shape of line diagram images of interest to mobile users may be of small file size (low details) or similar in size to the test images used in this study. They can therefore be transmitted with acceptable performance results in good mobile conditions. However, at a SNR of 10 dB, the subjective performance test results for both test images were seen to degrade (Table 5.7 to 5.10).

In addition to the effect of image file size, it was found that the shape of the transmitted image also affects the performance assessment. Observers have shown that the shape of the floor plan (test image 1) was visually more predictable in comparison to the campus map (test image 2), which contain more detailed information. Accordingly, the effect of errors was considered to be more serious on the test image 2.

B. The Effect of Vehicle Speed

In comparing the performance results at a low vehicle speed of 10 MPH, as shown in Tables 5.3, 5.5, 5.7, 5.9, with the results at a high vehicle speed of 50 MPH and the same channel parameters as shown in Tables 5.4, 5.6, 5.8, 5.10, it will be seen that a marked improvement is obtained at low vehicle speed. At low vehicle speed of 10 MPH, SNR 20 dB and a transmission rate 2400 bits/s, the average quality grades for the test images 1 and 2 are 4.51 and 4.24 (Table 5.3, error file 1) compared to 3.96 and 3.4 at high vehicle speed of 50 MPH (Table 5.4, error file 2). For lower values of SNR, such as 10 dB, the effect of high vehicle speed is severely disturbing. At SNR of 10 dB, transmission rate of 2400 bits/s and a low vehicle speed of 10 MPH, the average quality grade values for the test images 1 and 2 are 2.85 and 2.38 (Table 5.7, error file 5), compared to 1.93 (annoying) and 1.36 (very annoying) at high vehicle speed of 50 MPH (Table 5.8, error file 6). For corresponding channel parameters, the average erroneous shapes in the test images 1 and 2 are 4.4, 7.1 for a speed of 10 MPH and 7.75, 15.13 for a speed of 50 MPH.

The reason for the degradation of the subjective performance results at high vehicle speed is explained as follows. At low vehicle speed, long periods of good (nonfade) interval followed by relatively long fade intervals occur with a low rate of occurrence, while shorter periods are obtained at high speed but with higher rate of occurrence. Errors in these periods affect the transmitted image data as follows.

Nonfade Intervals

In these intervals, the probability of error is very small for normal values of SNR and errors occur randomly (see chapter 4). When an error occurs it may affect any bit position within the image file with equal probability. It is possible that the effect of a single error can be very small such that it cannot be recognized by the subjective test, e.g., when the error occurs in the least significant bit of a coordinate data of a drawing element. When an error occurs in the most significant bit of the coordinate data, then a large error or shift in the coordinate position is observed. It is also possible that the effect of a single error may be very disturbing. For example, when the error occurs in the bitstream of an opcode of a drawing element or in the bit 7 of a parameter data. The result of such an error might be a change in the type of the drawing element or missing the drawing element from the reproduced image. This effect is usually equivalent to that of a long burst of errors.

During the nonfade time intervals, the probability of an error occurring in the coordinate bits of a drawing element is higher than in the opcode bits or bit 7 of the coordinate data. This is because, within the data of a drawing element, more bits are assigned to the coordinate data. At normal values of SNR, the probability of errors in the nonfade periods is very small. However, at low values of SNR, the probability of errors increases and, as a result, errors occur mainly in the coordinate data of drawing elements, causing different erroneous shapes in the test image.

Fade Intervals

In these intervals, the probability of error is very high = 0.5. At low vehicle speed, long burst of errors occur, compared to shorter bursts at high speed. As an example, we shall consider the effect of the burst error length on the data of a drawing element of 7 bytes (1 byte opcode + 6 bytes parameter data). The effect of a burst error of 7 bits (1 byte) has usually the same effect as a long burst error of length equal to the drawing element , i.e., a burst error of 7 bytes (49 bits) length. This is because a burst error of 7 bits will certainly change the format of one complete code byte to an erroneous format within the drawing element. The long burst error of 7 bytes will change the format of more code bytes within the drawing element. In both cases the receiver protocol either deletes the erroneous drawing element, for the case when the erroneous element is not interpreted by the receiver protocol and hence the shape of the drawing element is missed, or it processes the erroneous shape, which results in an erroneous drawing shape in the reproduced image. It can be said, therefore, that a short burst error usually has the same effect on the data of drawing elements as a long burst error. A conclusion can be drawn that, at the same channel error-rate, the effect of a channel with random errors or short burst errors on the transmitted image file data will be much worse than the effect of a channel with longer burst errors. Because at high vehicle speed the rate of fade, and hence the rate of burst occurrence (although of short length) is high, then it is expected that the rate of erroneous drawing element at high speed is higher than at low vehicle speed. As a result, better performance results are obtained at low vehicle speed.

From Tables 5.3, 5.5, 5.7, 5.9 it will be seen that at low vehicle speed the results of the quality analysis are slightly better than the usefulness analysis. This is because of the effect of long burst errors at low vehicle speed. When a long burst error occurs in a drawing element, it is expected that it will change a large number of bits (depending on the burst length) in the drawing element to erroneous bits. As a result, the format of the drawing element is usually changed to an unknown format. The receiver cannot process or interpret the unknown format and thus ignores the erroneous data. The result is that the shape of the drawing element from the reproduced image is missing. If a short burst error has occurred, then it's effect may also be a missing drawing element or it produces an erroneous shape. From the quality point of view, missing a drawing element is not clearly noticeable by the observer but from the usefulness point of view it is usually a misleading error.

Figures 5.6 and 5.7 show typical results obtained when subjecting unprotected source coded data of the test images 1 and 2 to a mobile channel at SNR 20 dB, transmission rate 2400 bits/s and a vehicle speed of 10 MPH (error file 1). The effect of transmission errors result in missing drawing elements and error in coordinate data of an element. In the usefulness tests the positions of the errors are indicated, as mentioned previously, by a symbol (x). In Fig. 5.6, a text is missing from the test image 1. In Fig.5.7, errors cause a missing polygon shape and a shift in the coordinate data of another polygon in the test image 2. From the usefulness point of view, the missing shapes may be misleading. However, from the quality point of view, where the positions of the missing shapes are not indicated the effects are not clearly noticeable.

From Tables 5.4, 5.6, 5.8, 5.10, it will be seen that at high vehicle speed the results of the usefulness analysis are slightly better than the quality analysis. The reason for this is as follows. At high vehicle speed a high rate of short error bursts occurs, thus more drawing elements are corrupted by errors compared to low vehicle speed. The short burst of errors usually produces erroneous drawing elements and it may also cause missing drawing elements from the reproduced image. Errors in drawing elements, e.g., error in coordinate data of a drawing element, may not be acceptable from the quality point of view. However, it may be understandable and therefore not misleading from the usefulness point of view.

Figures 5.8 and 5.9 show typical results obtained when subjecting unprotected source coded data of the test images 1 and 2 to a mobile channel at SNR 20 dB, transmission rate 2400 bits/s and high vehicle speed of 50 MPH (error file 2). In Fig.5.8, transmission errors affect two line elements in the test image 1. Errors produce a very small shift in the coordinate data of the first line element and a comparatively larger shift in the second element. In Fig. 5.9, transmission errors affect 5 elements in the test image 2. The errors cause a small and large shift in the coordinates of two polygon elements, missing a line, a text and changing a line element to a marker element. From the quality point of view, errors in the coordinate data of the line element in Fig. 5.8 or the polygon shape in Fig.5.9 are annoying to a certain degree. However, from the usefulness point of view, it can be easily observed that the shift in the line or polygon coordinate is due to errors and the original shapes are understandable and therefore not misleading.

C. The Effect of Transmission Rate

Two values of transmission rate (2400 bits/s and 4800 bits/s) are considered. In comparing the results of transmission rate 2400 bits/s, SNR (10 dB, 20 dB) and vehicle speed (10 MPH, 50 MPH) as shown in Tables 5.3, 5.4, 5.7, 5.8 with the results of transmission rate 4800 bits/s having the same channel parameters as shown in Tables 5.5, 5.6, 5.9, 5.10, it can be seen that a slight improvement in the performance is obtained at the higher transmission rate of 4800 bits/s. For example, at the transmission rate of 2400 bits/s, SNR of 10 dB, low vehicle speed of 10 MPH, the average usefulness grades for the test images 1 and 2 are 2.7 and 2.23 (Table 5.7) compared to 3.23 and 2.57 (Table 5.9) at the transmission rate of 4800 bits/s.

The reason for this is as follows. At the transmission rate of 4800 bits/s, the average number of bits that occur in both the nonfade and fade periods are doubled compared to the transmission rate of 2400 bits/s, assuming the other channel conditions are kept constant. Under such conditions, it is expected that a larger number of test images (depends also on the image size and other mobile channel parameters) will be transmitted during the nonfade periods and consequently the transmitted images will arrive containing small errors or without errors. For example, at a transmission rate 2400 bits/s, SNR 20 dB and vehicle speed of 10 MPH, about 63.2 % of test image 1 and 50 % of test image 2 are graded 5 on the quality scale (Table 5.3) compared to 75.8 % of test image 1 and 55 % of test image 2 at transmission rate 4800 bits/s with the same channel parameters (Table 5.5)

During the fade periods, longer burst errors are produced at 4800 bits/s. However, if a long burst error occurs in a drawing element that contains a larger number of bits compared to the erroneous bits in the burst, then the burst will affect only one drawing element. This is equivalent to the case of a shorter burst error as in the case of the lower transmission rate of 2400 bits/s. This means that, although longer bursts of erroneous bits are produced at the higher transmission rate of 4800 bits/s, they are usually shorter than the length of the drawing elements. In such a case the effect of fade intervals on the transmitted image data at 2400 bits/s and 4800 bits/s is almost the same.

When the number of bits in the drawing element is smaller than the number of erroneous bits in the long burst, then the effect of the long burst will also be expanded to the next following drawing element, causing errors in at least two drawing elements. Under such conditions, it is possible that a small number of transmission test images will deteriorate severely due to long fade periods at 4800 bits/s.

Thus, at the higher transmission rate of 4800 bits/s, the performance during the nonfade periods improves and during the fade periods very similar results are obtained compared to the lower transmission rate of 2400 bits/s. As a result, better performance is obtained at higher transmission rate.

If an error correction method is used to protect the image file data, then it is expected that the case of long burst errors (high transmission rate) will usually require a more powerful error correction method compared to the case of shorter burst errors (low transmission rate). This conclusion is an advantage for the low transmission rate.

D. The Effect of SNR

In the survey results, two values of SNR are used (20 dB, 10 dB). The SNR was the most important factor that had an effect on the results of the subjective performance. It can be seen, as expected, that the performance results at the SNR of 20 dB (BER about 5×10^{-4}) as shown in Tables 5.3 to 5.6 are much better compared with the lower value of SNR 10 dB (BER about 5×10^{-3}) as shown in Tables 5.7 to 5.10. For example, at SNR 20 dB, transmission rate 4800 bits/s and a vehicle speed of 10 MPH, the average value of the usefulness grades for the test images 1 and 2 are 4.57, 4.22 (Table 5.5), compared to 3.23 and 2.57 at SNR of 10 dB (Table 5.9).

Under good mobile transmission conditions, the unprotected line diagram test images 1 and 2 were received with acceptable subjective performance grades. At a SNR of 20 dB and a low vehicle speed of 10 MPH, an average value of 4 or higher was obtained for both the quality and usefulness subjective tests of the test images 1 and 2 (Tables 5.3 and 5.5). At a SNR of 20 dB and a high vehicle speed of 50 MPH, the performance degrades in comparison to the low speed (Tables 5.4 and 5.6).

At a lower value of SNR 10 dB, the subjective performance degrades considerably. Fig. 5.10 and 5.11 indicate the results of transmitting the unprotected test images 1 and 2 over a mobile channel at a SNR of 10 dB, transmission rate 2400 bits/s and a vehicle speed of 10 MPH. In comparison to the case of SNR of 20 dB (Fig. 5.6 and 5.7), it can be seen that a larger number of geometric elements are affected by errors at an SNR of 10 dB, causing the general appearance of the test images to become slightly annoying or annoying from the quality point of view and slightly misleading or misleading from the usefulness point of view.

Figures 5.12 and 5.13 shows typical results obtained when subjecting unprotected test images 1 and 2 to a mobile channel at SNR 10 dB, transmission rate 2400 bits/s and high vehicle speed of 50 MPH. In comparison to the case of low vehicle speed of 10 MPH (Fig. 5.10 and 5.11), It can be seen that a larger number of drawing elements are affected and thus the performance degrades more severely.

The degradation in the results of the subjective performance at low SNR is due to the increase in the probability of errors during the nonfade intervals and the increase in the fade intervals, where both effects degrade the performance results. This indicates the need for protecting the transmitted source coded image data by a suitable channel error protection scheme.

E. Summary of Overall Subjective Performance Tests of the Unprotected Image Data

The summary of overall subjective performance tests of the unprotected source coded data for the test images 1 and 2 transmitted over mobile channels is given as follows, see Fig.5.4.

1. A better performance is obtained with test image 1 which is visually more predictable and smaller in file size compared to the test image 2.
2. Channel errors in the most significant bits of the parameter data give large error or shift in coordinate positions. However, errors in the least significant bits are usually unnoticable by the observers, especially in the high detail images, e.g., test image 2.
3. At the same channel error-rate, the effect of a channel with short burst errors or random errors on the transmitted image file is much worse than the effect of a channel with long burst errors. Therefore, a marked improvement in the performance is obtained at low vehicle speed where long error bursts occur over that obtained at high vehicle speed where shorter error bursts occur but with higher rates.
4. At a low vehicle speed of 10 MPH, the results of the quality analysis are slightly better than the usefulness analysis, while at a high vehicle speed of 50 MPH, the usefulness performance is better than the quality.
5. Higher transmission rate of 4800 bits/s results in a slight improvement in the performance compared to the low transmission rate of 2400 bits/s. It is possible, however, that a small number of transmission test images will deteriorate severely at high transmission rate of 4800 bits/s because of the large number of errors it contains.

6. The SNR is the most important factor that effects the performance analysis. At SNR of 20 dB and a low vehicle speed of 10 MPH, an acceptable performance was obtained. At SNR 10 dB, the average grades of the quality and usefulness analysis decreases sharply, especially at a high vehicle speed of 50 MPH.

5.4 Summary

In this chapter, the effect of errors deliberately introduced into various bit positions of the graphical elements was obtained. Based on this information, a receiver protocol was developed to process the received image file data corrupted with errors due to mobile transmission. The performance of the received line diagram test images was evaluated using the 5-point grade scale based on the CCIR Rec.500. The most significant factors affecting the performance results were the SNR and vehicle speed. Transmission rate and image file size and shape have also an effect, but less serious. To obtain an acceptable performance result for the transmitted test images, good channel conditions were required such as a high value of SNR (20 dB) and low vehicle speed. However, at a SNR of 20 dB and high vehicle speed of 50 MPH, the performance degrades. When the SNR is reduced to 10 dB, the subjective performance tests for both test images degrades considerably.

The results given in this chapter indicate that channel protection schemes are required to ensure that the transmitted encoded source data for the test images can cope with expected mobile channel conditions.

Table 5.3 Subjective performance analysis at SNR =20 dB, transmission rate = 2400 bits/s, vehicle speed = 10 MPH (error file 1)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	63.2	50	57.2	42
Grade 4	27.8	29.5	28.3	32.5
Grade 3	5.8	15.5	9.5	23
Grade 2	3.2	5	5	2.5
Grade 1	0	0	0	0
Average grade	4.51	4.24	4.37	4.14

Table 5.4 Subjective performance analysis at SNR =20 dB, transmission rate = 2400 bits/s, vehicle speed = 50 MPH (error file 2)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	43	20	48	25
Grade 4	18.6	28	30.3	33
Grade 3	30	26	13.6	31
Grade 2	8.3	24	8	11
Grade 1	0	2	0	0
Average grade	3.96	3.4	4.18	3.72

Table 5.5 Subjective performance analysis at SNR =20 dB, transmission rate = 4800 bits/s, vehicle speed = 10 MPH (error file 3)

Five-pointg rade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	75.8	55	72.7	45
Grade 4	19.2	29.2	15.8	35
Grade 3	4	14.2	7.6	17.5
Grade 2	1	1.6	4	2.5
Grade 1	0	0	0	0
Average grade	4.69	4.37	4.57	4.22

Table 5.6 Subjective performance analysis at SNR =20 dB, transmission rate = 4800 bits/s, vehicle speed = 50 MPH (error file 4)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	50.3	23	54	24
Grade 4	20.5	36	22.5	54
Grade 3	12.5	31	16.2	14
Grade 2	16.6	4	7.3	4
Grade 1	0	6	0	4
Average grade	4.06	3.66	4.23	3.9

Table 5.7 Subjective performance analysis at SNR =10 dB, transmission rate = 2400 bits/s, vehicle speed = 10 MPH (error file 5)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	7.6	0	5.2	0
Grade 4	21.2	18.7	19	7.5
Grade 3	34	23.7	31.2	33.7
Grade 2	23.2	35	30.2	33.7
Grade 1	14	22.5	14.4	25
Average grade	2.85	2.38	2.7	2.23

Table 5.8 Subjective performance analysis at SNR =10 dB, transmission rate = 2400 bits/s, vehicle speed = 50 MPH (error file 6)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	0	0	0	0
Grade 4	6	0	11	0
Grade 3	21	0	24.5	0
Grade 2	33.5	36.6	36.5	55
Grade 1	39.5	63.3	28	45
Average grade	1.93	1.36	2.18	1.55

Table 5.9 Subjective performance analysis at SNR =10 dB, transmission rate = 4800 bits/s, vehicle speed = 10 MPH (error file 7)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	13.6	4.7	12	2.3
Grade 4	34.4	25	33.4	13.1
Grade 3	31.4	25	23.2	34.5
Grade 2	17.6	40.5	28.6	39.3
Grade 1	3	4.7	2.8	10.7
Average grade	3.38	2.84	3.23	2.57

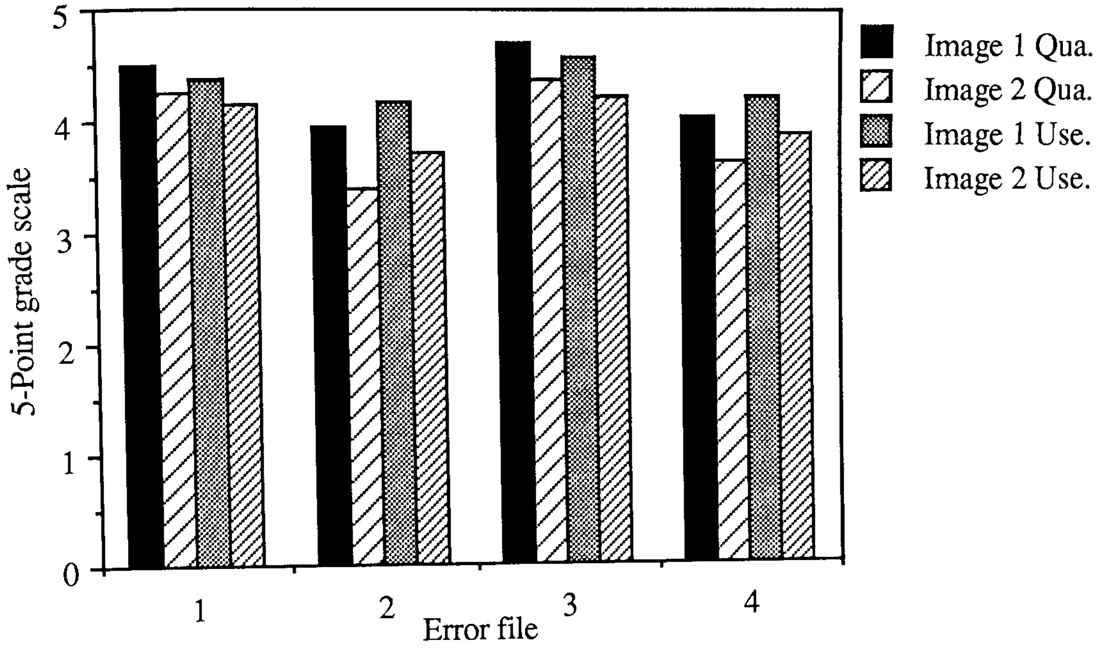
Table 5.10 Subjective performance analysis at SNR =10 dB, transmission rate = 4800 bits/s, vehicle speed = 50 MPH (error file 8)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	0.7	0	0	0
Grade 4	11	0	12.3	0
Grade 3	25	11.6	30	23.3
Grade 2	28.3	35	32.6	35
Grade 1	35	53.3	25	41.6
Average grade	2.14	1.58	2.3	1.81

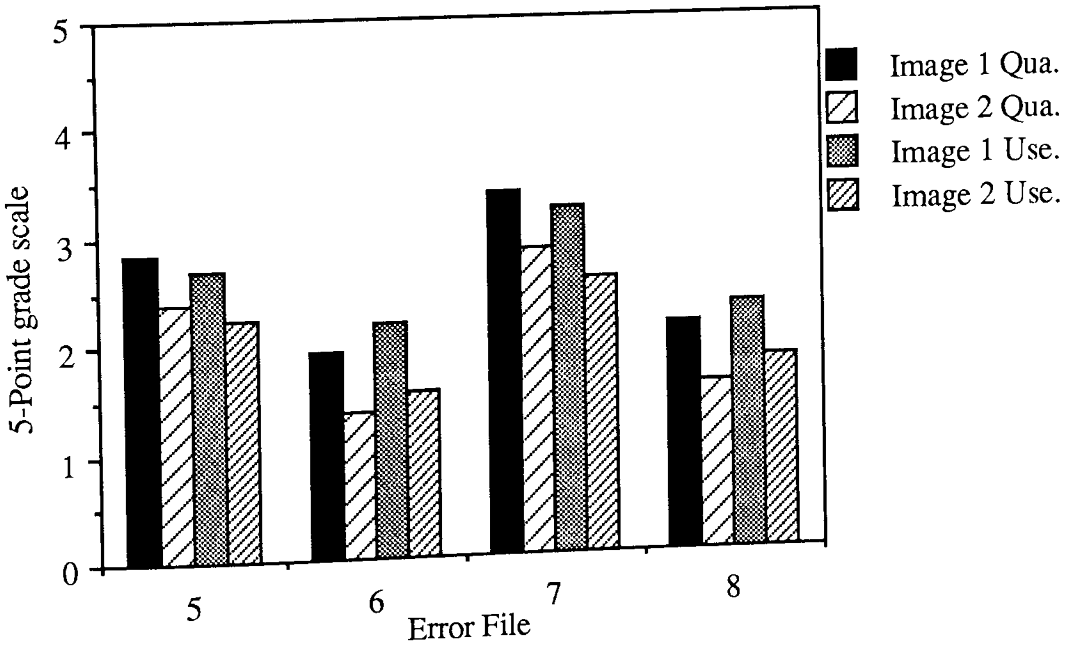
Table 5.11 Average number of erroneous elements in the test images 1 & 2 for various mobile channel conditions

Channel conditions	Average erroneous elements in image 1	Average erroneous elements in image 2	BER
Error file 1	0.88 = 1.54 %	1.36 = 1.49 %	5×10^{-4}
Error file 2	1.26 = 2.21 %	2.84 = 3.12 %	
Error file 3	0.64 = 1.12 %	1.06 = 1.16 %	
Error file 4	1.20 = 2.10 %	2.48 = 2.72 %	
Error file 5	4.40 = 7.71 %	7.10 = 7.8 %	5×10^{-3}
Error file 6	7.75 = 13.59 %	15.13 = 16.62 %	
Error file 7	2.66 = 4.66 %	6.05 = 6.65 %	
Error file 8	6.86 = 12.03 %	11.20 = 12.3 %	

Fig. 5.4 Transmission errors cause a missing polygon from the test image 2



(a) Error files 1 to 4
Error file 1 : SNR=20 dB, Rate = 2400 bits/s, Speed 10 MPH
Error file 2 : SNR=20 dB, Rate = 2400 bits/s, Speed 50 MPH
Error file 3 : SNR=20 dB, Rate = 4800 bits/s, Speed 10 MPH
Error file 4 : SNR=20 dB, Rate = 4800 bits/s, Speed 50 MPH



(b) Error files 5 to 8
Error file 5 : SNR=10 dB, Rate = 2400 bits/s, Speed 10 MPH
Error file 6 : SNR=10 dB, Rate = 2400 bits/s, Speed 50 MPH
Error file 7 : SNR=10 dB, Rate = 4800 bits/s, Speed 10 MPH
Error file 8 : SNR=10 dB, Rate = 4800 bits/s, Speed 50 MPH

Fig 5.5 Average Quality and Usefulness of the test images 1 and 2 versus error files (a) error files 1-4 (b) error files 5-8.

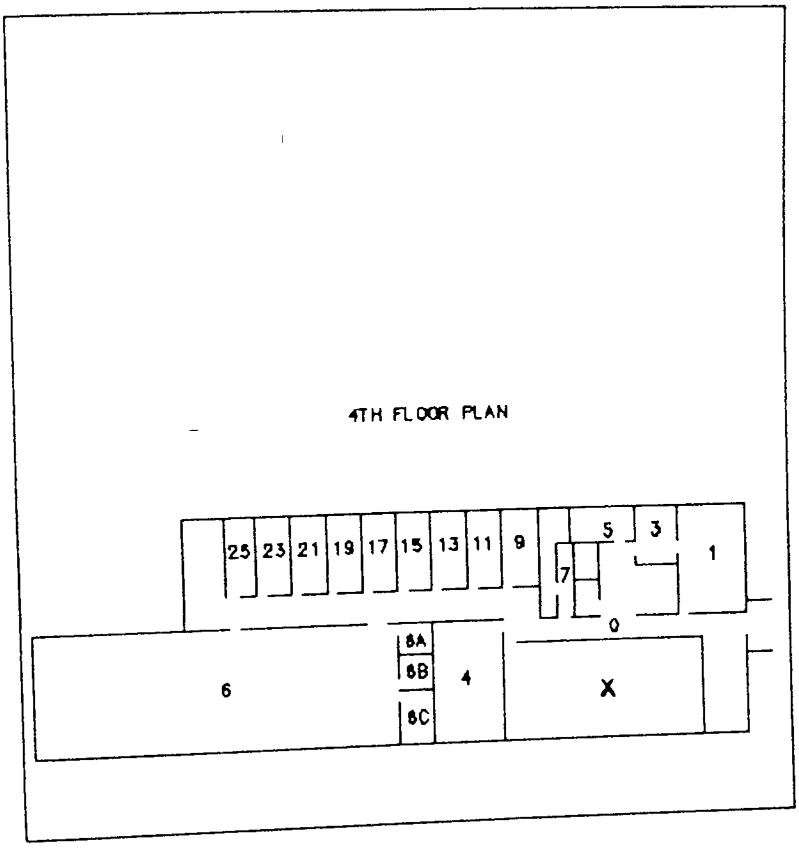


Fig. 5.6 Unprotected test image 1 subjected to mobile transmission errors (error file 1: SNR = 20 dB, transmission = 2400 bits/s, speed = 10 MPH)

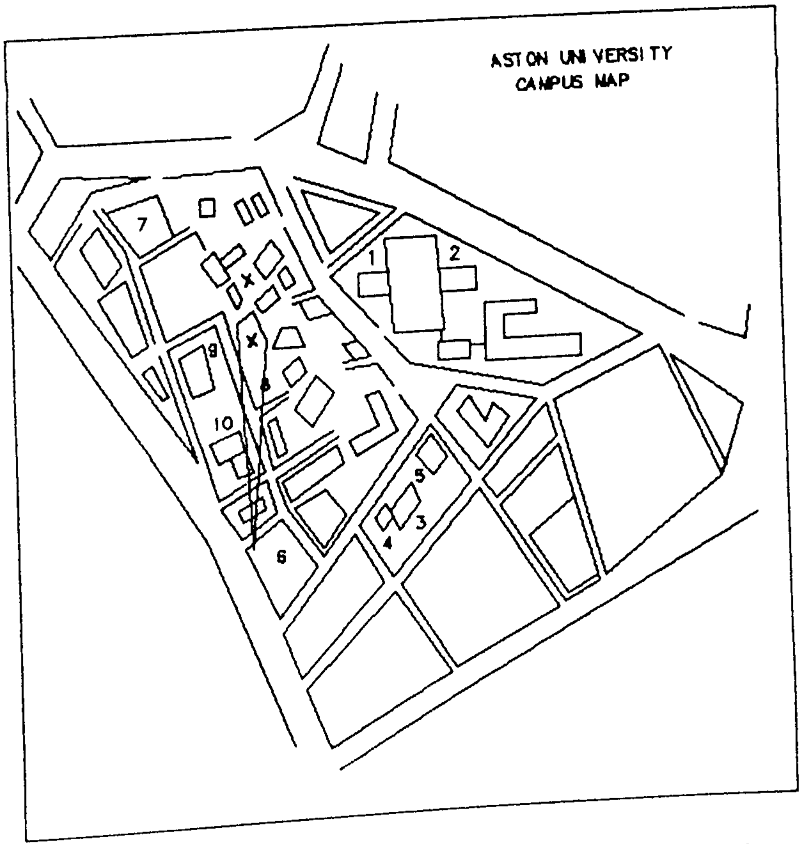


Fig. 5.7 Unprotected test image 2 subjected to mobile transmission errors (error file 1: SNR = 20 dB, transmission = 2400 bits/s, speed = 10 MPH)

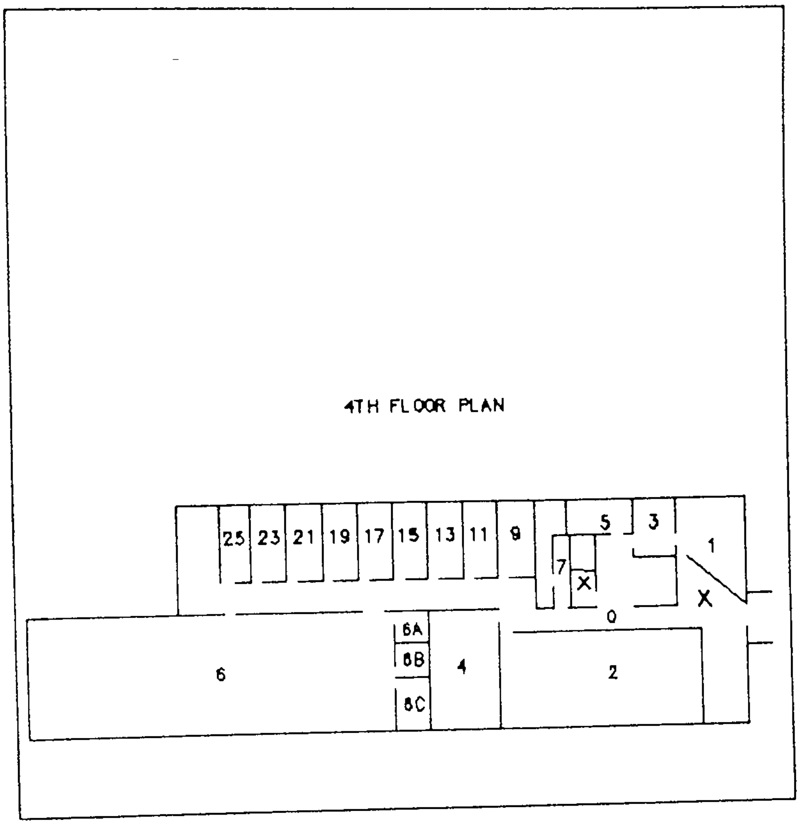


Fig. 5.8 Unprotected test image 1 subjected to mobile transmission errors (error file 2: SNR = 20 dB, transmission = 2400 bits/s, speed = 50 MPH)

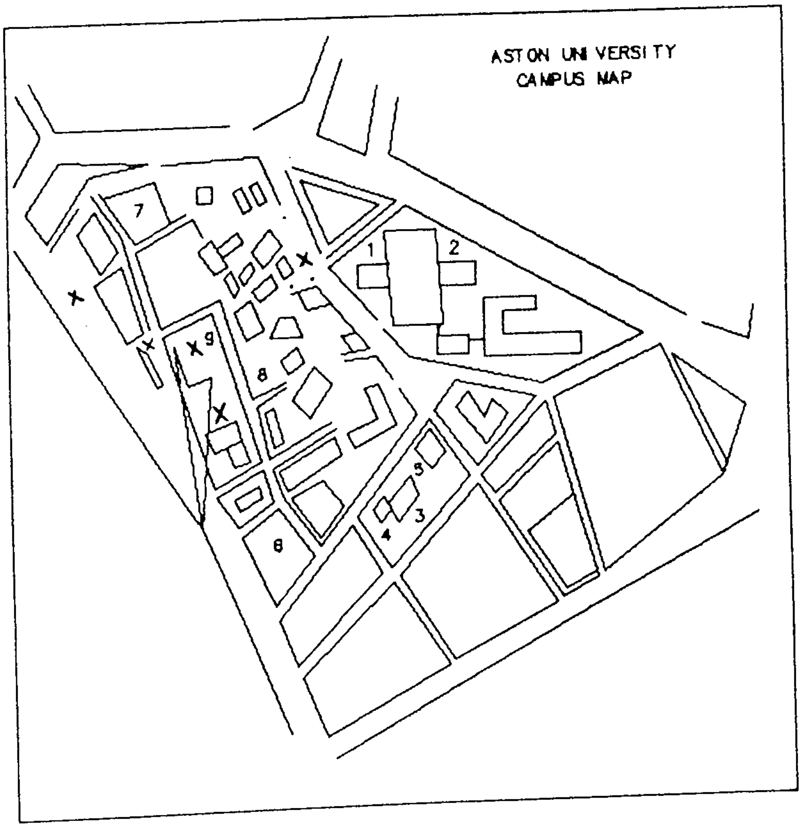


Fig. 5.9 Unprotected test image 2 subjected to mobile transmission errors (error file 2: SNR = 20 dB, transmission = 2400 bits/s, speed = 50 MPH)

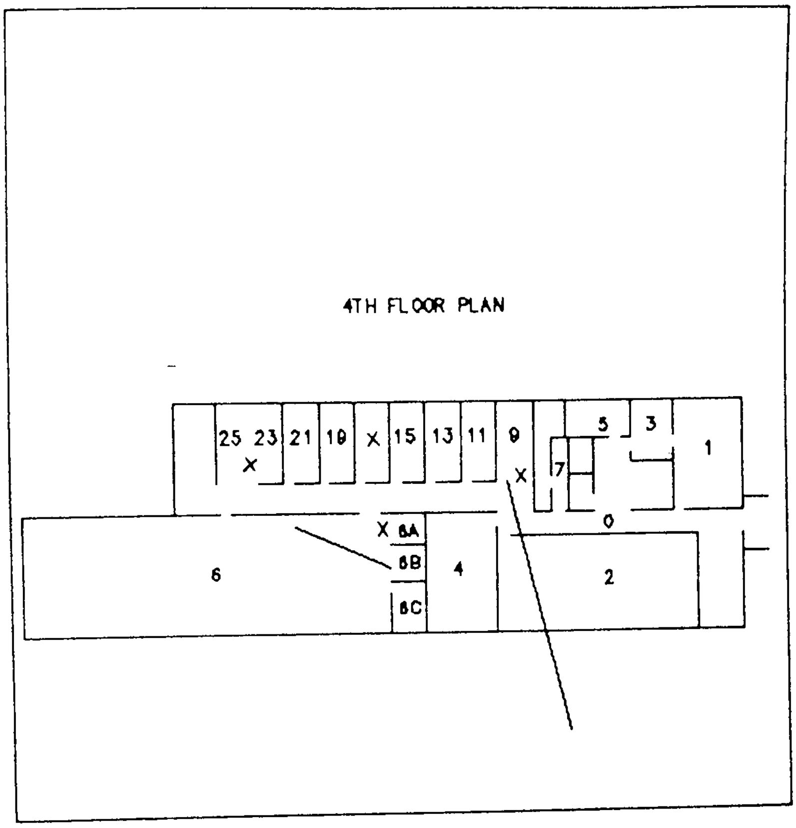


Fig. 5.10 Unprotected test image 1 subjected to mobile transmission errors (error file 5: SNR = 10 dB, transmission = 2400 bits/s, speed = 10 MPH)

Fig. 5.11 Unprotected test image 2 subjected to mobile transmission errors (error file 5: SNR = 10 dB, transmission = 2400 bits/s, speed = 10 MPH)

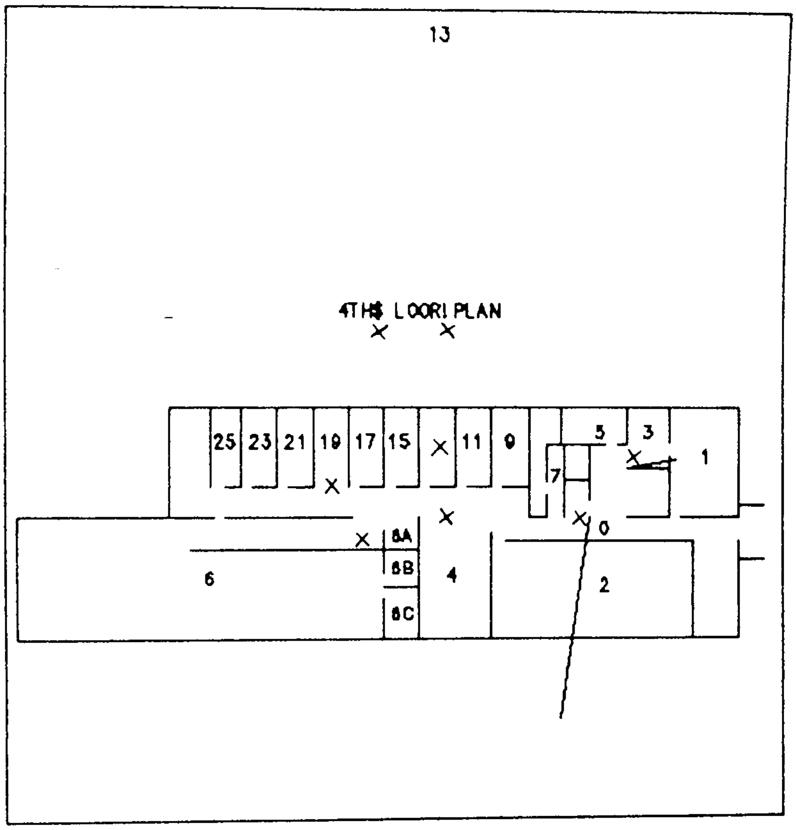


Fig. 5.12 Unprotected test image 1 subjected to mobile transmission errors (error file 6: SNR = 10 dB, transmission = 2400 bits/s, speed = 50 MPH)

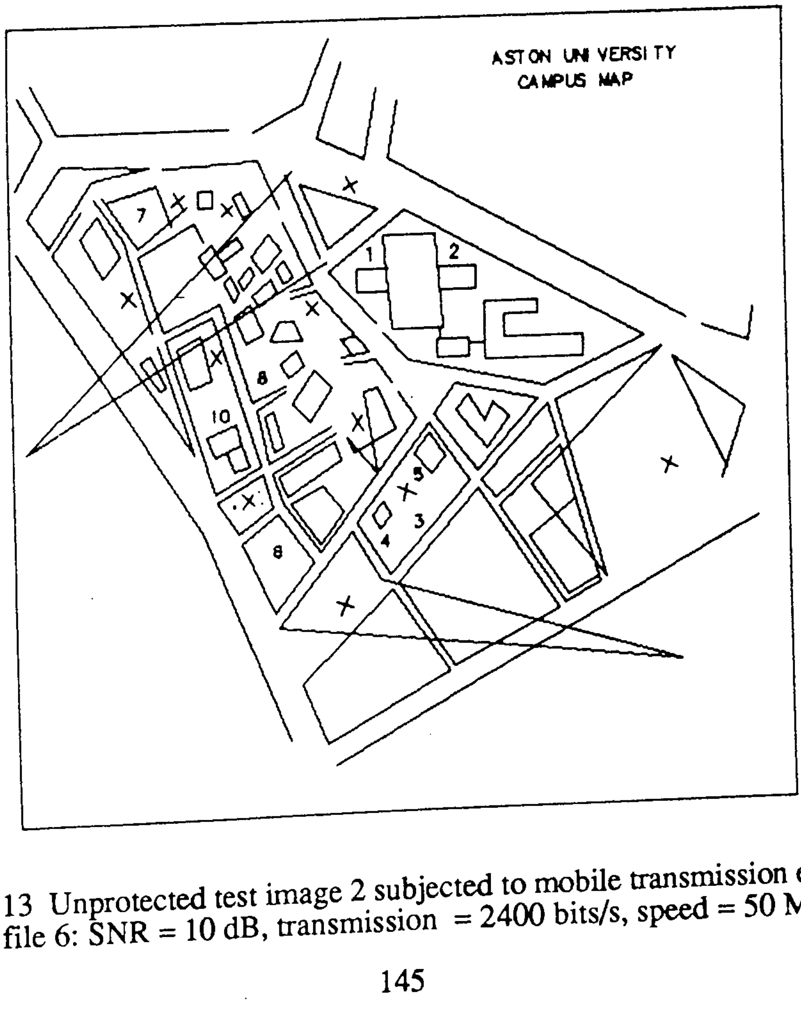


Fig. 5.13 Unprotected test image 2 subjected to mobile transmission errors (error file 6: SNR = 10 dB, transmission = 2400 bits/s, speed = 50 MPH)

CHAPTER 6

ERROR CONTROL TECHNIQUES IN DIGITAL COMMUNICATION SYSTEMS

6.1 Introduction

In chapter 5 we described the subjective performance tests of the transmitted unprotected image data over mobile channels. We have also seen how errors can occur in the transmitted image file data because of various mobile channel impairments. To attain acceptable performance results, the mobile channel should be operated under good conditions such as a SNR of 20 dB or higher (BER = $5x10^{-4}$ or lower) and low vehicle speed. However, over mobile channels these conditions cannot be kept constant and, as a result, the performance degrades. Faced with this problem, and in order to obtain an acceptable subjective performance of the transmitted images under expected mobile conditions or bad channel conditions such as a low value of SNR 5 dB (BER about $1.7x10^{-2}$), the practical solution is the use of error control techniques.

Error control is an area of increasing importance in communication systems. In 1948, Shannon showed that, by proper encoding and decoding of the information data, the probability of error in the transmitted data can be made arbitrarily low. Error control techniques enable a transmission system to approach reliable performance, despite the presence of noise. In these techniques, some additional redundant digits are transmitted with the information digits over the channel. These additional digits, while conveying no new information themselves, make it possible for the receiver (decoder) to detect or correct errors in the information digits. The amount of redundancy needed depends on the proportion of errors acceptable after the decoding operation and on whether it is necessary to locate errors so that they can be corrected or whether a general indication that there is an error in a message block is sufficient. The noise causes errors in both the transmitted information and redundant digits. If the error control technique has been well designed, then there is usually enough information available to the receiver to allow a decoder to detect or correct most of the errors, unless the noise or interference on the channel is extremely severe.

In digital communication systems there are two basic categories of error control techniques. These are the Forward Error Correction (FEC) techniques and Automatic Repeat Request techniques (ARQ) [21-24]. In the communication context, both techniques add redundancy to data information before transmission in order to reduce the effect of errors that occur during transmission. However, the ideas behind each technique are quite different. In an FEC technique, redundancy is added to the source data so that a decoder can correct the errors at the receiver. Note that an FEC technique does not need a return path. An ARQ technique utilizes redundancy to detect errors and, when detected, it requests a repeat transmission. A return path is therefore necessary. Forward error correction codes require considerably more redundancy than ARQ codes, which are designed simply to detect the presence of errors. Both FEC and ARQ techniques have been used widely for providing reliable data transmission over mobile channels [48, 68, 111, 114-116] and therefore are used in this study to protect the source image subjected to errors caused by mobile channels. We shall restrict our study of error correction and detection codes to binary data since our source image data is in the binary format. In the following sections we consider the FEC and ARQ techniques in more detail.

6.2 Forward Error Correction Techniques (FEC)

In this strategy, an error correcting code is used for correcting transmission errors. The process of coding involves adding some redundant (parity-check) digits into the source data to form a codeword based on the code used by the strategy. When the receiver detects the presence of errors in a received code, it attempts to correct the errors. After the error correction has been performed, the decoded data is then delivered to the user. If the receiver fails to correct the errors, the received data block will be incorrectly decoded and erroneous data will be delivered to the user. Since no retransmission is required in an FEC strategy, no feedback channel is needed and the throughput efficiency of the system is maintained at constant level equal to the rate of the code used regardless of the channel error rate.

In an FEC system, the larger the code block the more efficient the code becomes, but the probability of errors in the block increases with block size. Hence there is a trade-off, in which there will be an optimum block size for given channel conditions. If the data is not in blocks, then a convolution code operating on continuous data may be used for this situation. In this study, an FEC system using block codes is used. This is because the source coded image data is represented by code bytes, where each byte consists of 7 bits, see chapter 3.

In a real communication channel, the type of error correction code used is highly dependent upon the form the error patterns take. If errors occur randomly, a random error correcting code can be used. If the errors are not random, the random error correcting code will not perform well. Therefore, the channel error patterns and error-rate statistics should be analysed to determine whether or not the errors are random, and what type of coding is necessary. For channels with random errors and with a specified error-rate it is possible to achieve high system reliability using a proper random error correcting code which can correct a specific number of errors in a data block. The number of errors in a block is estimated from the error-rate statistics. For channels where errors occur in bursts, then burst error correcting codes are most appropriate. Computer simulation (see chapter 4) and field measurements [59, 60] indicate that mobile channels are characterized by having bursty error patterns caused by fading due to multipath propagation. In mobile channels there are in general three types of error correcting codes used to combat burst errors.

1. Use random error correction coding and transmit the codeword repeatedly for a number of times, as for example, in the coding techniques used in mobile communication systems such as the advanced mobile phone system [49]. The main drawback of this category is that, because of the repeated transmission of the same codeword, system efficiency is low.
2. Use burst error correcting codes. Burst correcting codes perform well on the classic bursty channel where error bursts are rarely longer than a certain number of bits and are

separated by error-free guard spaces which are rarely shorter than a certain number of bits. However, there is a restricted usefulness of burst error correcting on mobile channels. This is because the variation in fade duration produces error bursts which are very unpredictable in length [48, 111].

3. Use random error correction coding with interleaving [48, 66, 111]. The main disadvantage of this category is that the interleaved codes cannot be used when the message length is small. Moreover, interleaving increases the delay of the system. However, this category can be implemented very simply.

The technique used in this study for protecting the transmitted image data over mobile channels is to use interleaving to turn burst errors into effectively random errors and then applying a proper random error correcting code [117]. However, we need to study the effect of the interleaving disadvantages in more detail (short messages and system delays). In this study, the file size of the transmitted test images is long enough (3507 bits and 7595 bits) for long interleaved codes to be implemented. With respect to system delay, it is expected that this could cause undesirable effects in the case of speech transmission. However, in the transmission of image data, it is to be expected that the delays introduced by interleaving will be negligible in comparison to the normal time required in viewing the received line diagram image.

FEC codes, however, have some drawbacks. To work efficiently, the errors introduced by the channel in a codeword should not exceed a certain number, depending on the code used. If errors increase then erroneous data will be delivered. In order to attain high reliability, a powerful error correcting code must be used. Information about the channel error-rate statistics and error patterns is also needed so that the code can correct the errors in the transmission. Another disadvantage of error correction codes is the large amount of redundancy usually required for these codes. Despite these drawbacks, in some situations, where it is impossible to provide a feedback link, only the FEC system is applicable.

In the followings sections related to FEC techniques, a description of basic linear block codes and cyclic block codes used for correcting random errors is given. We then deal with the decoding of the cyclic block error correcting codes. The majority-logic decodable codes are presented for the decoding procedure. Interleaving techniques for handling mobile bursty error channels are also discussed.

6.2.1 Linear Block Codes

In block codes, the binary information data is segmented into message blocks, each block consists of k information digits. The encoder transforms a message block into a larger block of $n > k$ bits by adding (n-k) check digits derived from the k bits message. The encoded n bits block is called a codeword. In a linear block encoding the (n-k) check digits are generated from linear combinations of the message bits k and the encoding operation can be performed using Boolean matrix algebra [22, 118-123]. All the codes used in this study are linear.

Let the message block be a row vector $D = (d_1, d_2, \ldots\ldots\ldots, d_k)$, where each message bit can be a 0 or 1. Thus there are 2^k distinct message blocks. Each message block is transformed to a codeword $C = (c_1, c_2, \ldots, c_n)$ of length n bits by the encoder and there are 2^k codewords, one unique codeword for each distinct message block. The rate efficiency of this (n, k) block code is k / n. In a systematic linear block code, the first k bits of the codeword are the message bits,

i.e., $c_i = d_i \quad , \quad i = 1, 2, \ldots\ldots\ldots, k$

The last n-k bits in the codeword are check bits generated from the k message bits according to some predetermined rule. Thus the codewords satisfy the equation

$$\left[c_1, c_2, \ldots, c_n\right] = \left[d_1, d_2, \ldots, d_k\right] . \begin{bmatrix} 1\ 0\ 0 \ldots 0\ p_{11}\ p_{12} \cdots p_{1,\ n-k} \\ 0\ 1\ 0 \ldots 0\ p_{21}\ p_{22} \cdots p_{2,\ n-k} \\ 0\ 0\ 1 \ldots 0\ p_{31}\ p_{32} \cdots p_{3,\ n-k} \\ 0\ 0\ 0 \ldots 1\ p_{k1}\ p_{k2} \cdots p_{k,\ n-k} \end{bmatrix} \qquad (6.1)$$

or, $C = D.G$

where G is the [k x n] matrix and is called the generator matrix of the code and it has the form $G = [\, I_k . P]_{k \times n}$. The matrix I_k is the identity matrix of order [k x k] and P is an arbitrary [k .(n-k)] matrix. The coefficients $p_{i,j}$ are 0 s and 1 s. When P is specified, it defines the (n, k) block code completely. An important step in the design of a (n, k) block code is the selection of a P matrix so that the code generated by generator matrix G has certain desirable properties such as ease of implementation and the ability to correct errors. The encoder of a linear block code should perform the following: store the generator matrix G, or at least the submatrix P, and perform binary operations to generate the check bits. Obviously the complexity of the encoder increases as the block size n and the number of check bits increase.

For each (n, k) linear block code there is a parity check matrix H, which is defined as $H = [\, P^T . I_{n-k}]_{(n-k) \times n}$. The parity check matrix can be used to verify whether a codeword C is generated by the matrix G. In a linear (n, k) code with a generator matrix G and parity check matrix H, C is a code word if and only if

$$C . H^T = 0 \qquad (6.2)$$

where H^T is the transpose of the matrix H. Let C be a code vector transmitted over a noisy channel and let R be the received noise corrupted vector. The vector R is the sum of the original code vector C and an error vector E, i.e.,

$$R = C + E \tag{6.3}$$

The receiver does the decoding operation by determining a vector S defined as

$$S = R \, . \, H^T \tag{6.4}$$

The vector S is called the error syndrome of R. Thus

$$S = [\, C + E \,] \, . \, H^T$$

$$S = C \, . \, H^T + E \, . \, H^T$$

Since $\quad C \, . \, H^T = 0$

then $\quad S = E \, . \, H^T$

Thus the syndrome of a received vector is zero if R is a valid code vector. If errors occur in transmission, then the syndrome S of the received vector is nonzero. Furthermore, S is related to the error vector E and the decoder uses S to detect and correct errors in the received code as will be shown later. Equation (6.4) is the basis of almost all decoding methods.

In order to characterize the error detecting or correcting capability of a linear code a distance must be defined. The best known and most used distance in channel theory is the Hamming distance [124, 125]. The Hamming weight of a code vector C is defined as the number of nonzero components of C and the Hamming distance between two vectors C_1 and C_2 is defined as the number of components in which they differ. The minimum distance of a block code is the smallest distance between any pair of codewords in the code. In general it can be shown that a linear block code with a minimum (Hamming) distance d can correct up to [(d-1) / 2] errors or detect up to (d -1) errors in each code word.* Hamming codes are capable of correcting single errors and are considered as a special case of the linear block codes. They have the following parameters:

$n = 2^m - 1, \;\; k = n - m, \;\; t = 1$

where n, k, t are the block length, number of information digits and error correcting capability respectively and $m \geq 2$ is the number of parity check digits in the code.

* where $[x]$ = largest integer $\leq x$.

6.2.2 Binary Cyclic Codes

Binary cyclic codes form a subclass of linear block codes. The identifying feature of a cyclic code is the property that a cyclic shift of any codeword results in another codeword from the set. Cyclic codes are the most extensively studied class of block codes. These codes have considerable mathematical structure that makes it possible to design codes with useful error correcting properties. Cyclic block codes have been widely investigated, and many powerful codes with simple encoding and decoding procedures are known. In cyclic codes the elements of a codeword are treated as the coefficients of a polynomial of degree n-1. Thus, the codeword V is represented by a code polynomial as

$$V(x) = v_0 + v_1 \, x + v_2 \, x^2 + ... + v_{n-1} \, x^{n-1}$$

A cyclic code is defined in terms of a generator polynomial g(x) of a code of degree (n-k). To encode a message polynomial m(x), we divide x^{n-k} m(x) by g(x) and then add the remainder resulting from this division to x^{n-k} m(x) to form the code polynomial;

$$x^{n-k} . \, m(x) = q(x) \, . \, g(x) + r(x) \qquad (6.5)$$

where q(x) is the quotient and r (x) is the remainder resulting from dividing. Thus,

$$V(x) = x^{n-k} . \, m(x) + r(x)$$

where V(x) is the encoded message. Writing out $r(x) + x^{n-k} . m(x)$, we have

$$r(x) + x^{n-k} . \, m(x) = r_0 + r_1 \, x + ... + r_{n-k-1} \, x^{n-k-1}$$
$$+ m_0 \, x^{n-k} + m_1 \, x^{n-k+1} + ... + m_{k-1} \, x^{n-1} \qquad (6.6)$$

which corresponds to a systematic codeword, in which the first n-k symbols are the parity check symbols and the last k symbols are the information symbols.

It is also possible to encode a message block into a cyclic code using the generator matrix. The generator matrix of a cyclic code in systematic form can be formed as follows. Dividing x^{n-k+i} by the generator polynomial g(x) for i = 0, 1, .., k-1, we obtain

$$x^{n-k+i} = q_i(x)\, g(x) + r_i(x) \tag{6.7}$$

where, $r_i(x) = r_{i0} + r_{i1}\, x + r_{i2}\, x^2 + ... + r_{i,n-k-1}\, x^{n-k-1}$

Thus the polynomials $V(x) = r_i(x) + x^{n-k+i}$ for i = 0, 1,..., k-1 are code polynomials. Arranging these k code polynomials as k rows of a matrix we obtain the generator matrix G of the cyclic code as follows [22, 118].

$$G = \begin{bmatrix} r_{00} & r_{01} & r_{02} & \cdots r_{0,n-k-1} & 1\,0\,0 \ldots 0 \\ r_{10} & r_{11} & r_{12} & \cdots r_{1,n-k-1} & 0\,1\,0 \ldots 0 \\ r_{20} & r_{21} & r_{22} & \cdots r_{2,n-k-1} & 0\,0\,1 \ldots 0 \\ r_{k-1,0} & r_{k-1,1} & r_{k-1,2} & \cdots r_{k-1,n-k-1} & 0\,0\,0 \ldots 1 \end{bmatrix} \tag{6.8}$$

From Eq.(6.8), the parity check matrix H of the cyclic code can also obtained.

A binary cyclic encoded message containing errors can be represented by R(x) = V(x) + E(x), where V(x) is the correct encoded message and E(x) is a polynomial which has a non-zero term in each erroneous position. To detect errors, we divide the received erroneous message R(x) by the generator polynomial g(x), in which the remainder is the syndrome code. If the received message R(x) is not dividable by g(x), the syndrome is non-zero, then an error has occurred. If R(x) is divisible by g(x), the syndrome is zero, then no error or an undetectable error has occurred. The syndrome code contains information about the error pattern in the received code which is used for error correction.

Bose-Chaudhuri-Hocquenghem Codes (BCH)

An important sub-class of cyclic codes are the BCH codes. These are extensively used and are considered to be the most powerful error correcting cyclic codes. For any positive integers m and t ($t < 2^{m-1}$) there exists a BCH code with the following parameters:

Block length: $n = 2^m - 1$

Number of parity-check digits: $n-k \leq m t$

Minimum distance: $d \geq 2t + 1$

This code is capable of correcting any combination of t or fewer errors in a block of $n = 2^m - 1$ digits.

The generator polynomial of a BCH code is obtained as follows [22, 118, 126].

Let α be a primitive element of the Galois field $GF(2^m)$. Let $m_i(x)$ be the minimum polynomial of α^i, $0 \leq i \leq 2t$. Then the generator polynomial of the t-error-correcting BCH code is the least common multiple (LCM) of the $m_i(x)$, i odd, i.e.,

$$g(x) = LCM\,(\, m_1(x),\ m_3(x), \ldots\ldots, m_{2t-1}(x)\,) \qquad (6.9)$$

The generator for a BCH code for $t = 2$, $m = 4$, $GF(2^4)$ is given by :

$$g(x) = LCM\,(\, m_1(x),\ m_3(x)\,)$$

To find $m_1(x)$, the following sequence is generated using the Galois field $GF(2^4)$:

$$\alpha,\ \alpha^2,\ \alpha^4,\ \alpha^8,\ \alpha^{16} = \alpha,\ \alpha^{32} = \alpha^2$$

In this sequence, there are only four distinct elements α, α^2, α^4, α^8

Thus $m_1(X)$ has α, α^2, α^4, and α^8 as all its roots, and

$$m_1(x) = (x + \alpha)(x + \alpha^2)(x + \alpha^4)(x + \alpha^8)$$

Multiplying out the right-hand of the above equation with the aid of the Galois field GF(2^4), we obtain

$$m_1(x) = 1 + x + x^4$$

In the same manner; $m_3(X)$ has α^3, α^6, α^9, and α^{12} as all its roots, and

$$\begin{aligned} m_3(x) &= (x + \alpha^3)(x + \alpha^6)(x + \alpha^9)(x + \alpha^{12}) \\ &= 1 + x + x^2 + x^3 + x^4 \end{aligned}$$

Thus, the generator polynomial of the double-error-correcting BCH code of length $n = 2^4 - 1 = 15$ is given by:

$$\begin{aligned} g(x) &= \mathrm{LCM}(m_1(x),\ m_3(x)) \\ &= m_1(x)\ m_3(x) \\ &= (1 + x + x^4)(1 + x + x^2 + x^3 + x^4) \\ &= 1 + x^4 + x^6 + x^7 + x^8 \end{aligned}$$

The double-error-correcting code is a (15, 7) cyclic code with minimum distance $d \geq 5$. This code corrects two errors or less in a codeword of $n = 15$ bits, in which $n-k = 8$ bits are the parity check bits and $k = 7$ bits are information bits. We use this code later for simulation study.

6.2.3 Majority-Logic Decodable Codes

In the last section we have considered the binary cyclic error correction codes and the encoding methods. The BCH codes as a sub-class of the cyclic codes were also given. In forward error correction techniques, the important factor to be considered is the decoding operation. The decoding of error correction codes is a much more difficult task than the encoding. Therefore, when selecting an error correcting code, it is important to choose the code in which the decoding operation can be implemented easily either by hardware or software.

Majority-logic decodable codes form a smaller sub-class of the cyclic codes than do the BCH codes. Also they are slightly inferior to the latter in terms of error correcting ability for values of code length and efficiency. However, the main advantage of majority-logic decodable codes is that the decoding operation is very simply implemented, often much more simply than the BCH codes [22, 118, 119, 127]. For this reason the majority-logic decodable codes are used in this study for protecting the transmitted source coded image data. In this section we give a brief discussion of the concept of orthogonal parity check sums which will be used in the decoding algorithm and then describe the decoding procedure for the majority-logic codes.

Let $E = (e_0, e_1, ..., e_{n-1})$ be a received codeword vector corrupted with transmission errors.

The syndrome is given by $S = E \cdot H^T = (s_0, s_1, .., s_{n-k-1})$.

Consider a sum of syndrome bits,

$A = a_0 s_0 + a_1 s_1 + ... + a_{n-k-1} s_{n-k-1}$

where a_i is either 0 or 1. The sum A is called a parity-check sum. A set of parity-check sums is said to be orthogonal on a particular bit position if that bit is involved in every sum in the set and no other bit is involved in more than one sum. Thus the set of parity-check sums in Eq. (6.10) is orthogonal on the bit e_0.

$$\begin{array}{l} e_6 + e_3 + e_0 \\ e_5 + e_2 + e_0 \\ e_4 + e_1 + e_0 \end{array} \qquad (6.10)$$

If it is possible to construct a set of J parity-check sums orthogonal on a particular bit in a cyclic code with minimum distance d then, because of the cyclic properties of the code, such a set can be constructed on every bit. When J = d-1, then the code is said to be completely orthogonalizable in one step. The algorithm of the parity-check sums orthogonal on every bit is used in the decoding procedure, and is now given as an example. Consider the (15, 7, 2) BCH binary cyclic code which is simulated in this study. The code has been selected among majority-logic decodable codes. The code has a minimum distance d=5 and its generator polynomial is given by [22, 118];

$$g(x) = 1 + x^4 + x^6 + x^7 + x^8$$

From Eq.6.8, the parity check matrix H [n-k x n] for the code is given by:

$$H = \begin{bmatrix} 1&0&0&0&0&0&0&0&1&1&0&1&0&0&0 \\ 0&1&0&0&0&0&0&0&0&1&1&0&1&0&0 \\ 0&0&1&0&0&0&0&0&0&0&1&1&0&1&0 \\ 0&0&0&1&0&0&0&0&0&0&0&1&1&0&1 \\ 0&0&0&0&1&0&0&0&1&1&0&1&1&1&0 \\ 0&0&0&0&0&1&0&0&0&1&1&0&1&1&1 \\ 0&0&0&0&0&0&1&0&1&1&1&0&0&1&1 \\ 0&0&0&0&0&0&0&1&1&0&1&0&0&0&1 \end{bmatrix}$$

For the received codeword with error pattern $E = e_0, e_1, \ldots\ldots, e_{14}$, the syndrome bits, $S = E.H^T = (s_0, s_1, \ldots., s_7)$ are given by;

$$s_0 = e_0 + e_8 + e_9 + e_{11}$$

$$s_1 = e_1 + e_9 + e_{10} + e_{12}$$

$$s_2 = e_2 + e_{10} + e_{11} + e_{13}$$

$$s_3 = e_3 + e_{11} + e_{12} + e_{14}$$

$$s_4 = e_4 + e_8 + e_9 + e_{11} + e_{12} + e_{13}$$

$$s_5 = e_5 + e_9 + e_{10} + e_{12} + e_{13} + e_{14}$$

$$s_6 = e_6 + e_8 + e_9 + e_{10} + e_{13} + e_{14}$$

$$s_7 = e_7 + e_8 + e_{10} + e_{14}$$

From the eight syndrome bits, four (i.e., d-1) parity-check sums orthogonal on the leading bit e_{14} can be performed as follows ;

$$A_1 = s_3 \qquad = e_3 + e_{11} + e_{12} + e_{14}$$

$$A_2 = s_1 + s_5 \qquad = e_1 + e_5 + e_{13} + e_{14}$$

$$A_3 = s_0 + s_2 + s_6 \quad = e_0 + e_2 + e_6 + e_{14}$$

$$A_4 = s_7 \qquad = e_7 + e_8 + e_{10} + e_{14}$$

It can be seen that the leading bit e_{14} is checked by all four sums and no other digit is checked by more than one sum. For explanation, assume that all the transmitted bits of the codeword = 0, i.e., the received vector E represents only error digits due to the transmission channel. If $\{t < [(d-1) / 2]\}$ errors occurred and one of them occurred in e_{14}, i.e., $e_{14} = 1$, then at least three (or a majority, $\geq [(d+1) / 2]$) of the four sums are equal to 1. If e_{14} was not in error, then at most $[(d-1) / 2]$ sums will be 1. The results of the four check-sums are applied to a majority logic decision algorithm where the output of the majority logic is 1 if and only if more than one-half the sums are 1; otherwise, the output is zero, see Fig. 6.1. The output is the estimated value of an error digit and is used to correct the first leading digit e_{n-1} of the codeword.

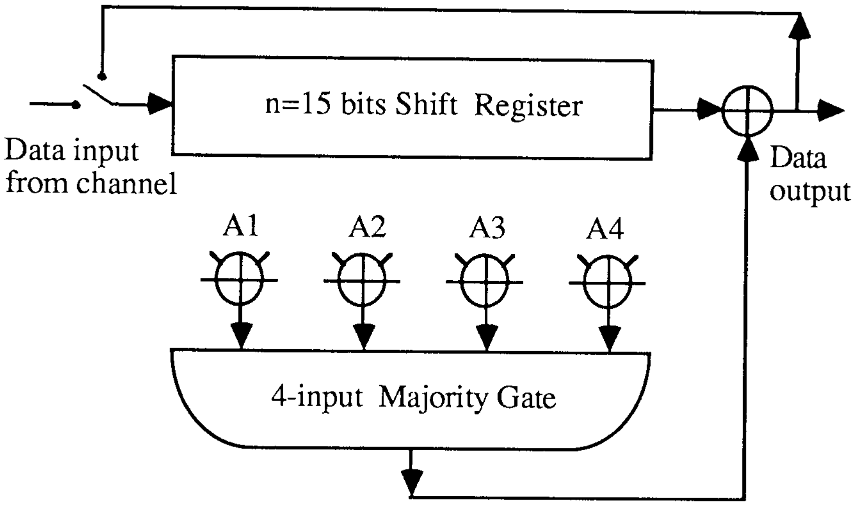


Fig. 6. 1 Decoder for the (15, 7, 2) majority-logic code (one-step decoder)

After decoding the first leading digit e_{n-1} then it is shifted one step and hence becomes the last digit in the codeword. Because the code is cyclic, then the second digit e_{n-2}, which has now become the first leading digit in the codeword, is corrected exactly as the first digit e_{n-1}. The process of shifting and error correction is repeated a total of n times until all errors in the codeword have been corrected. Correct decoding is guaranteed provided that (d-1) / 2 or fewer errors occurred in the received codeword. The decoding algorithm described above is called one-step majority-logic decoding.

Based on the majority-logic decoding two other cyclic codes selected among majority-logic decodable codes have been simulated for this study.

- A longer (73, 45, 4) difference-set cyclic code, which corrects four or less errors in a codeword of n=73 bits, using 28 parity check bits and 45 information bits.
- A shorter (7, 4, 1) Hamming code which corrects one error in a codeword of n=7 bits, using 3 parity check bits and 4 information bits.

In the following, we describe the procedure for obtaining the parity-check sum equations orthogonal on the first leading (highest-order) bit e_{n-1} of the above two codes.

The (73, 45, 4) Difference-Set Cyclic Code

The minimum distance of this code is d= 10 and the generator polynomial of the code is given by [22, 118].

$$g(x) = 1 + x^2 + x^4 + x^6 + x^8 + x^{12} + x^{16} + x^{22} + x^{25} + x^{28}$$

The (73, 45, 4) cyclic code is classified within the class of difference-set codes among majority-logic decodable codes. Difference-set codes are nearly as powerful as the other known cyclic codes. However, there are relatively few codes within this group. A simple perfect difference-set of order $q=p^s$, where p is prime and s is a positive integer, is defined as a collection of q integers chosen from the set [0,1,...., q] such that no two of the ordered difference sets are identical, i.e., each occurs once [128]. In this section we shall only be concerned with the algorithm adopted to derive the orthogonal equations used for decoding the (73, 45, 4) code. For more details about these codes the reader may refer to the books by Lin [22, 118], Peterson [121] and the paper by Weldon [128].

Let $P = [l_0 = 0, l_1, l_2, ..., l_q]$ be a perfect simple difference set of order $q = p^s$, where p is considered equal to 2 for binary codes. A difference-set code of length n is defined as the cyclic code represented by the generator polynomial g(x):

$$g(x) = \frac{(x^n + 1)}{h(x)} \tag{6.11}$$

$$= 1 + g_1 x + g_2 x^2 + ... + x^{n-k}$$

where h(x) is called the parity polynomial of the cyclic code generated by g(x). This code has the following parameters:

Code length : $n = 2^{2s} + 2^s + 1$

Number of parity check digits : $n\text{-}k = 3^s + 1$

Minimum Distance : $d = 2^s + 2$

Define the following polynomial:

$$z(x) = 1 + x^{l_1} + x^{l_2} + ... + x^{l_q} \tag{6.12}$$

Let h(x) be the greatest common divisor (GCD) of z(x) and $x^n + 1$, i.e.,

$$h(x) = \mathrm{GCD}[z(x), x^n + 1]$$

$$h(x) = 1 + h_1 x + h_2 x^2 + ... + x^k \tag{6.13}$$

Let $h'(x) = x^k h(x^{-1})$ be the reciprocal polynomial of h(x). Then h'(x) is the null space of the difference set code generated by g(x). Let

$$\begin{aligned} z'(x) &= x^{l_q} z(x^{-1}) \\ &= 1 + ... + x^{l_q - l_2} + x^{l_q - l_1} + x^{l_q} \end{aligned} \tag{6.14}$$

Since z(x) is divisible by h(x), z'(x) is divisible by h'(x). Thus z'(x) is the null space of the difference set code generated by g(x). Let

$$\begin{aligned} w(x) &= x^{n-1-l_q} z'(x) \\ &= x^{n-1-l_q} + ... + x^{n-1-l_2} + x^{n-1-l_1} + x^{n-1} \end{aligned} \tag{6.15}$$

w(x) is divisible by h(x) and is also in the null space of the difference-set code generated by g(x). Now let

$$\begin{aligned} w^{(i)}(x) = {} & x^{l_i - l_{i-1} - 1} + x^{l_i - l_{i-2} - 1} + ... + x^{l_i - l_1 - 1} + x^{l_i - 1} \\ & + x^{n-1-l_q + l_i} + x^{n-1-l_{q-1} + l_i} + ... + x^{n-1} \end{aligned} \tag{6.16}$$

be the vector obtained by shifting w(x) cyclically to the right l_i times. Since $[l_0 = 0, l_1, l_2, ..., l_q]$ is a perfect difference set, then no two polynomials $w^{(i)}(x)$ and $w^{(j)}(x)$, for i not equal j, can have any common term except x^{n-1}. Thus, $w(x)$, $w^{(1)}(x)$, ..., $w^{(q)}(x)$ form a set of $J = d-1= 2^s +1$ polynomial orthogonal on the leading digit e_{n-1}. For the code (73, 45, 4), $s = 3$, and the perfect difference set $P = (0, 2, 10, 24, 25, 29, 36, 42, 45)$ [118]. Thus,

$$z(x) = 1 + x^2 + x^{10} + x^{24} + x^{25} + x^{29} + x^{36} + x^{42}+ x^{45}$$

$$z'(x) = x^{l_q}\ z(x^{-1})$$

$$z'(x) = x^{l_q}(1+ x^{-2} + x^{-10} + x^{-24} + x^{-25} + x^{-29} + x^{-36} + x^{-42} + x^{-45})$$

$$\begin{aligned} z'(x) &= x^{45}(1+ x^{-2} + x^{-10}+ x^{-24} + x^{-25} + x^{-29} + x^{-36} + x^{-42} + x^{-45}) \\ &= x^{45} + x^{43}+ x^{35}+ x^{21}+ x^{20}+ x^{16}+ x^{9}+ x^{3}+ 1 \end{aligned}$$

$$\begin{aligned} w(x) &= x^{n-1-l_q}\ z'(x) \\ &= x^{73-1-45}\ z'(x) \end{aligned}$$

$$\begin{aligned} w(x) &= x^{27}(1 + x^{3} + x^{9} + x^{16} + x^{20} + x^{21} + x^{35} + x^{43}+ x^{45}) \\ &= x^{27} + x^{30} + x^{36} + x^{43} + x^{47} + x^{48} + x^{62} + x^{70} + x^{72} \end{aligned}$$

By shifting $w(x)$ cyclically to the right 2 times ($l_1 = 2$), we obtain $w^1(x)$ as follows.

$$w^1(x) = x^{l_1-1} + x^{n-1-l_q+l_1} + x^{n-1-l_{q-1}+l_1} + x^{n-1-l_{q-2}+l_1} + \ldots.+ x^{n-1}$$

$$\begin{aligned} w^1(x) = {} & x^{2-1} + x^{73-1-45+2}+ x^{73-1-42+2} + x^{73-1-36+2} + x^{73-1-29+2} \\ & + x^{73-1-25+2} + x^{73-1-24+2} + x^{73-1-10+2} + x^{73-1} \end{aligned}$$

$$w^1(x) = x + x^{29}+ x^{32} + x^{38}+ x^{45} + x^{49} + x^{50} + x^{64} + x^{72}$$

In the same procedure and by shifting $w(x)$ cyclically to the right $l_2=10$, $l_3=24$, $l_4= 25$, $l_5= 29$, $l_6= 36$, $l_7= 42$, $l_8= 45$ we obtain the following equations $w^2(x)$, $w^3(x)$, $w^4(x)$, $w^5(x)$, $w^6(x)$, $w^7(x)$, $w^8(x)$ orthogonal on the digit e_{n-1} respectively. The final results of the equations are given as follows;

$$w^2(x) = x^7 + x^9 + x^{37} + x^{40} + x^{46} + x^{53} + x^{57} + x^{58} + x^{72}$$

$$w^3(x) = x^{13} + x^{21} + x^{23} + x^{51} + x^{54} + x^{60} + x^{67} + x^{71} + x^{72}$$

$$w^4(x) = 1 + x^{14} + x^{22} + x^{24} + x^{52} + x^{55} + x^{61} + x^{68} + x^{72}$$

$$w^5(x) = x^3 + x^4 + x^{18} + x^{26} + x^{28} + x^{56} + x^{59} + x^{65} + x^{72}$$

$$w^6(x) = x^6 + x^{10} + x^{11} + x^{25} + x^{33} + x^{35} + x^{63} + x^{66} + x^{72}$$

$$w^7(x) = x^5 + x^{12} + x^{16} + x^{17} + x^{31} + x^{39} + x^{41} + x^{69} + x^{72}$$

$$w^8(x) = x^2 + x^8 + x^{15} + x^{19} + x^{20} + x^{34} + x^{42} + x^{44} + x^{72}$$

From these 9 orthogonal polynomials we can form the following parity-check sums orthogonal on $e_{n-1} = e_{72}$,

$$A_1 = e_{27} + e_{30} + e_{36} + e_{43} + e_{47} + e_{48} + e_{62} + e_{70} + e_{72}$$

$$A_2 = e_1 + e_{29} + e_{32} + e_{38} + e_{45} + e_{49} + e_{50} + e_{64} + e_{72}$$

$$A_3 = e_7 + e_9 + e_{37} + e_{40} + e_{46} + e_{53} + e_{57} + e_{58} + e_{72}$$

$$A_4 = e_{13} + e_{21} + e_{23} + e_{51} + e_{54} + e_{60} + e_{67} + e_{71} + e_{72}$$

$$A_5 = e_0 + e_{14} + e_{22} + e_{24} + e_{52} + e_{55} + e_{61} + e_{68} + e_{72}$$

$$A_6 = e_3 + e_4 + e_{18} + e_{26} + e_{28} + e_{56} + e_{59} + e_{65} + e_{72}$$

$$A_7 = e_6 + e_{10} + e_{11} + e_{25} + e_{33} + e_{35} + e_{63} + e_{66} + e_{72}$$

$$A_8 = e_5 + e_{12} + e_{16} + e_{17} + e_{31} + e_{39} + e_{41} + e_{69} + e_{72}$$

$$A_9 = e_2 + e_8 + e_{15} + e_{19} + e_{20} + e_{34} + e_{42} + e_{44} + e_{72}$$

It can be seen that e_{72} is checked by all nine parity sums and no other digit is checked by more than one sum. According to the decoding procedure of the majority-logic decodable code, when more than 5 ones appear among $A_1, \dots, A_9$, the leading bit is erroneous, so this is corrected. In one-step decoding these orthogonal equations are used for correcting 4 or less errors in a codeword n = 73 bits.

The (7, 4, 1) Hamming Code

This is a Hamming code generated by $g(x) = 1 + x + x^3$. The parity check matrix H of this code is given by

$$H = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 \end{bmatrix}$$

The syndrome $s = (s_0, s_1, s_2) = e.H^T$ is given by,

$$s_0 = e_0 + e_3 + e_5 + e_6$$

$$s_1 = e_1 + e_3 + e_4 + e_5$$

$$s_2 = e_2 + e_4 + e_5 + e_6$$

It can be seen that only s_0 and s_2 parity check sums are orthogonal on the leading digit e_6. This code therefore cannot be decoded using a one-step majority logic algorithm. A set of parity check sums orthogonal on a single digit can be performed using a 2-step majority decoding algorithm. Let $E_1 = (e_5, e_6)$ and $E_2 = (e_4, e_6)$ be two sets orthogonal on e_6. The check sums s_0 and s_2 are orthogonal on set E_1 and the check sums $(s_0 + s_1)$ and s_2 are orthogonal on set E_2. The check sums (s_0, s_2) and $[(s_0 + s_1), s_2]$ are fed into the first two separate level majority decoding gates respectively as shown in Fig.6.2. This is the first step of decoding. The two outputs (J=2) of the first level which are orthogonal on e_6 are then fed into the second level of majority logic decoding gates and the output of the second level is used to correct e_6. Therefore, this code of a minimum distance d=3 correct any single error using the 2-step majority-logic decoding algorithm.

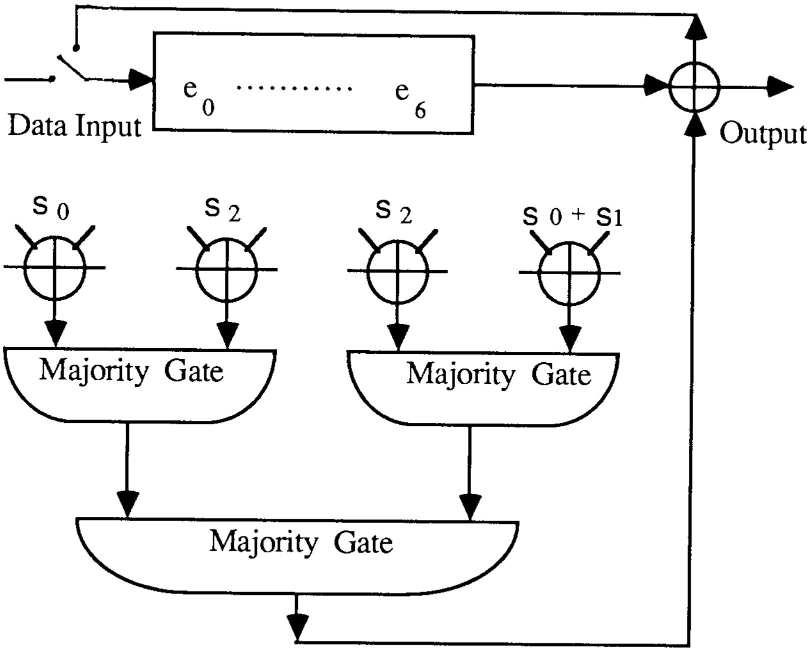


Fig. 6.2 Decoder for the (7, 4, 1) majority-logic code (two-step decoder)

6.2.4 Interleaving Techniques

In mobile communication systems a well-known and simple technique for handling burst errors is to use error correcting codes with interleaving [48, 51, 52, 53, 66, 111]. The basic idea of interleaving is to randomise the bursty error patterns which are introduced by the transmission channel. Interleaving the coded message before transmission and deinterleaving after reception causes bursts of channel errors to be spread out in time and hence enabling the random error correcting codes to be useful in a burst noise channel [129-133].

A typical interleaving scheme consists of an array of matrix elements of m codewords each n bits long. At the transmitter, the interleaver is filled by codewords on a row by row basis. When the array is filled, the data is then transmitted by column basis. The idea behind this technique is that adjacent bits in the same code words are separated during transmission by (m-1) bits. At the receiver, the deinterleaver performs the inverse operation. The data is entered into the deinterleaver array on a columns basis and read out on a row basis so that the original codewords are reproduced for decoding. The number of interleaved codewords m is called the interleaving degree (depth) which gives an indication of the length of error burst to be treated. The total number of bits (m.n) is called the interleaving period. Thus, if the error correcting code is capable of correcting a total of three random errors in a codeword, then a burst of three columns in length (3m) would be completely correctable. A higher degree of interleaving gives increased protection against long bursts of errors such as would occur in slow moving vehicles, but causes a longer delay. The interleaving degree m is selected so that burst errors introduced into the data stream will become random when taken at the output of the deinterleaving and hence the performance of the error correction code applied will be dramatically improved.

A chosen performance can be achieved in several ways by using different combinations of interleaving period and error correction complexity. In this study it was decided to use relatively simple error correction codes based on majority-logic decoding codes as explained earlier with an acceptable interleaving period. In the following chapter the performance of the three error correcting codes described earlier with various interleaving degree will be simulated to obtain a suitable combination used for protecting the transmitted image data.

6.3 Automatic Repeat Request Techniques (ARQ)

In an ARQ error control technique, an error detecting code is used for detecting transmission errors that occur during the transmission of messages or blocks of data in data transmission systems. When a message of k information bits is ready for transmission, n-k parity check bits are appended to it to form a codeword. These n-k parity checks are formed based on the code used by the system and are used for detecting transmission errors. The transmitted codeword may be affected by transmission errors and the received codeword may contain errors. When a codeword is received, the receiver computes its syndrome. If no errors are detected in a received codeword (i.e., the syndrome is zero), the received codeword is assumed to be error-free and is delivered to the user. At the same time, the receiver notifies the transmitter, via a return channel, and the next codeword will be transmitted. If the syndrome of the received word is not zero, the presence of errors is detected. In this case, the receiver discards the erroneously received codeword and requests a retransmission of the same codeword via a return channel. Retransmissions continue until the codeword is successfully received. An erroneous codeword is delivered to the user only if the receiver fails to detect the presence of errors. Using a suitable error detecting code, the probability of an undetected error can be made very small [21, 22].

The ARQ scheme is widely used in data communication because it is simple and it provides high system reliability reasonably independent of the channel quality. This high reliability is a result of retransmitting those messages or blocks found in error by the receiver. However, as the channel error-rate increases, ARQ error control techniques yield lower and lower throughput and the time delay of supplying data to the user is increased. There is a tradeoff, therefore, in selecting the length of the transmitted message or block of data. On the one hand, it is desirable to select the largest block length to minimize the time wasted in acknowledgments and associated delay. On the other hand, it is desirable to select the smallest possible block length to minimize the time wasted in block retransmissions. Another disadvantage of ARQ is that each data packet in the case of stop-and-wait ARQ, or packets in the case of selective-repeat ARQ, have to be stored at the receiver to be checked for error detection before they become available to the user.

There are three basic types of ARQ schemes: the stop-and-wait ARQ, the go-back-N ARQ, and selective-repeat ARQ. In a stop-and-wait ARQ error-control system, the transmitter sends a codeword to the receiver and waits for an acknowledgment (Ack) from the receiver before sending the next codeword, See Fig. 6.3. If either a negative acknowledgment (Nack) or no Ack arrive, the transmitter resends the same codeword and again waits for an acknowledgment. Retransmissions continue until the transmitter receives an Ack. This system is simple and is well suited to land mobile radio channels where idle time is short due to short link lengths. However, the system becomes ineffective for channels with long idle time due to long link propagation delays. This ineffectiveness can be overcome by using a go-back-N ARQ system which is based on continuous transmission strategies. In a go-back-N ARQ system, codewords are transmitted continuously. When a Nack is received, the transmitter stops sending new codewords. It backs up to the codeword that is negatively acknowledged and resends that codeword and the succeeding codewords. The main drawback of go-back-N ARQ is that, whenever a received codeword is detected in error, the receiver also rejects the next received codewords although many of them may be error free. This inefficiency can be overcome by using the selective-repeat ARQ system. In a selective-repeat ARQ system, codewords are also transmitted continuously. However, the transmitter only resends those codewords that are negatively acknowledged, see Fig. 6.4. After resending a Nack'ed codeword, the transmitter continues transmitting new codewords. A sufficient buffer must be provided at the receiver to store the error-free codewords following a received word detected in error because the codewords must be delivered to the user in the correct order. When the first Nack'ed codeword is successfully received, the receiver then releases any error free codewords in correct order from the buffer until the next erroneously received word is found.

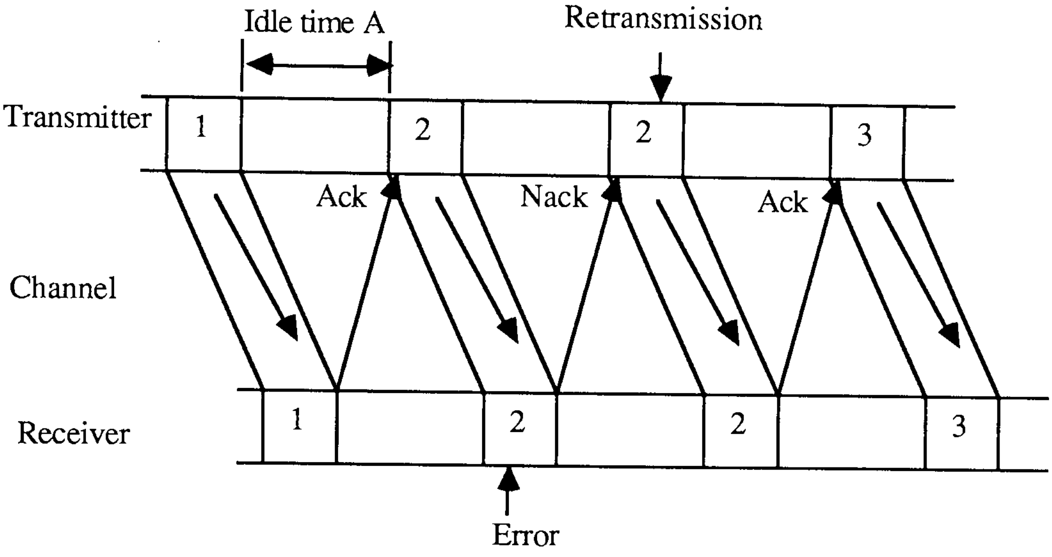


Fig. 6.3 ARQ technique (stop-and-wait).

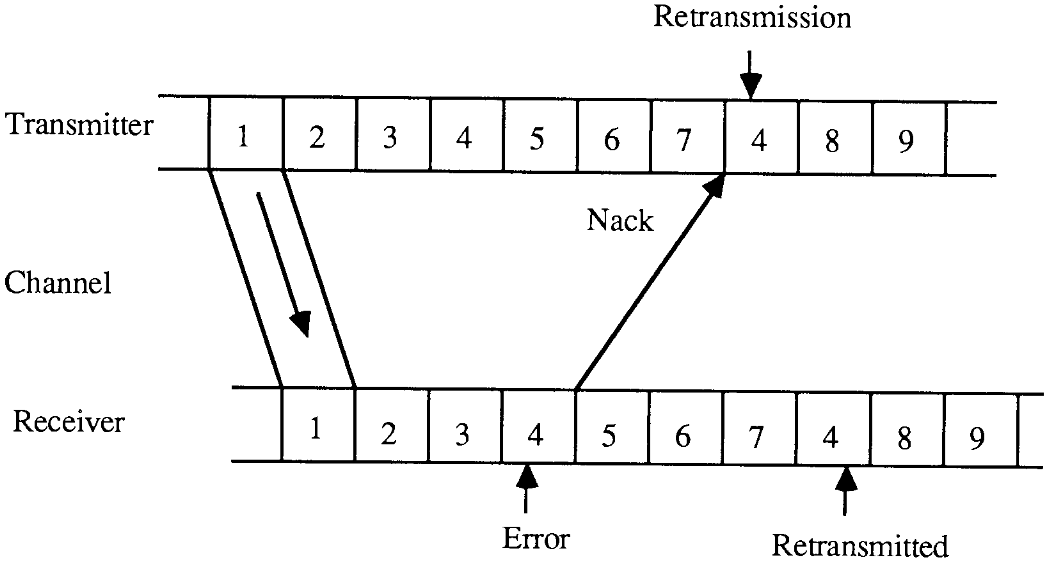


Fig. 6.4 ARQ technique (selective-repeat).

ARQ techniques have been used extensively to obtain reliability in data transmission systems. In mobile communications an important problem is how to provide reliable data transmission to users. As shown before, the mobile channel exhibits a wide range of signal quality. ARQ techniques therefore have been used widely to explore this problem [39, 68, 100]. In this study, two types of ARQ system were used to protect the transmitted image data over mobile channels. These are the stop-and-wait ARQ and the selective-repeat ARQ. In these systems, image file data stored in the metafile at the transmitter is decomposed into a number of packets. The transmitter sends either one packet of image data at a time and waits for an acknowledgment from the receiver before proceeding to send further data as in the stop-and-wait system, or a group of packets as in the selective-repeat system. Each packet consists partly of image data and partly of overhead data used for error detection and packet addressing.

6.3.1 Performance of the ARQ Techniques

In this study the performance of the ARQ techniques is evaluated in terms of the transmission time required to transmit an image file data over a mobile channel and the channel throughput. Because mobile channels exhibit a wide range of signal quality, an optimum packet length arises from the simulation that gives optimum system performance under certain specific mobile channel parameters. This is because short packets suffer from the proportionately greater number of overhead bits and long packets have a low probability of correct transmission.

In the following we examine the transmission time required for an image file to be transmitted over a mobile channel and the channel throughput for both the stop-and-wait ARQ and the selective-repeat ARQ systems. The numerical values obtained from the computer simulation are presented in chapter 7.

Let M be the image file size stored at the transmitter in bits

B be the packet length in bits

b be the overhead packet length in bits

R be the transmission rate in bits/s

Let T_p be the time required to transmit a data packet plus the overhead data. Thus

$$T_p = \frac{B+b}{R} = \frac{L}{R} \text{ seconds}$$

where $L = B+b$ bits

Let A be the timeout interval or the idle time of the transmitter, which is defined as the time-delay between the end of transmission of one packet and the end of reception of the corresponding acknowledgment from the receiver, see Fig. 6.3. In general, the timeout interval A is equal to the round-trip propagation delay ($2\,t_p$) plus receiver processing time (t_{proc}) plus the time required to transmit an acknowledgment t_s [2] , i.e.,

$$A = 2\,t_p + t_{proc} + t_s \tag{6.17}$$

The round-trip propagation delay from transmitter to receiver (t_p) and from receiver to transmitter (t_p) is small and therefore negligible due to the short link lengths in mobile communications. The term t_{proc} is the time delay required by the receiver to process the received data for error-detection plus the delay to change from receive to transmit mode in order to transmit the acknowledgment signal. In communication systems using full-duplex transmission mode, both the receiver and the transmitter can send and receive data at the same time. Also, the delay-time for the error-detection process at the receiver is very small. Therefore, in full-duplex mode the timeout or idle time delay is due almost entirely to acknowledgment delay, i.e.,

$$A = t_s = \frac{b}{R} \text{ (seconds)} \tag{6.18}$$

In systems using the half-duplex transmission mode, the delay-time for error detection at the receiver is also small. However, the receiver requires some delay, which can be anything between 100 msec and one second, to change from the receive mode to the transmit mode in order to send the acknowledgment. This delay is much longer than t_s. Therefore, in the half-duplex mode, the timeout delay or the idle time may be represented by a constant delay which depends on the switching time of the receiver, i.e., $A = t_{proc.}$ In this study, we consider a communication system with the full-duplex transmission mode. We now consider the following two ARQ systems.

Stop-and-Wait ARQ System

In the stop-and-wait ARQ system the expected acknowledgment time (T_1) for a packet transmitted over a mobile channel is equal to the first acknowledgment time plus the expected retransmission time and reacknowledgment time and is given by [134].

$$T_1 = A + \sum_{i=0}^{\infty} [\, P(\geq 1, L)\,]^i \,.\, [\, A + \frac{L}{R}\,] \qquad (6.19)$$

where L = B+b is the packet size in bits, b is the overhead data and is considered to be 32 bits. Also, $P(\geq 1, L)$ = packet error rate, which is the probability that a packet of L bits transmitted over the mobile channel will have at least one error. The packet error rates were extracted from error files for various mobile channel parameters, see chapter 4. Finally, A = the acknowledgment delay time.

Since $0 \leq P(\geq 1, L) \leq 1$, and $L > 0$, then,

$$\sum_{i=0}^{\infty} [\, P(1\geq, L)]^i = \frac{P(1\geq, L)}{1\text{-}P(1\geq, L)}$$

Thus, Eq.(6. 19) can be written as:

$$T_1 = A + [\, \frac{P(\geq 1, L)}{1 - P(\geq 1, L)}\,].[\, A + \frac{L}{R}\,] \qquad (6.20)$$

The image file size of M bits is partitioned into fixed size blocks of B bits per packet. Thus the number of packets per image file is (M / B).

Thus, in the stop-and-wait ARQ technique, the transmission time required to transmit an image of size M bits over a mobile channel is given by:

$$T_{t1} = [\frac{M}{B}] \cdot [T_1 + T_p]$$

$$T_{t1} = [\frac{M}{B}] \cdot [\frac{L}{R} + A + (\frac{P(1\geq, L)}{1 - P(\geq 1, L)}) \cdot (A + \frac{L}{R})] \qquad (6.21)$$

The throughput efficiency of an ARQ system is defined as the ratio of the average number of information bits successfully accepted by the receiver to the total number of bits that could be transmitted during the same period of time. For the stop-and-wait ARQ the throughput efficiency E_1 is given by [21, 22, 135, 136]:

$$E_1 = [\frac{B}{L + AR}] . [1 - P(1\geq, L)] \qquad (6.22)$$

For the full-duplex mode, $A = b / R$ and Eq.(6.22) becomes:

$$E_1 = [\frac{B}{L + b}] \cdot [1 - P(1\geq, L)] \qquad (6.23)$$

Selective-Repeat ARQ System

In this system, packets are transmitted continuously without waiting for acknowledgment and each unconfirmed packet data is retransmitted. To determine the transmission time required to transmit an image file data we refer back to Eq. (6.20) used for the stop-and-wait ARQ. In the selective-repeat ARQ system there is no need to confirm the reception of each packet and hence for the reverse channel the acknowledgment delay $A = 0$ [134]. In the stop-and-wait ARQ there is always a fixed delay (A) due to acknowledgment of each packet through the reverse channel as shown by the first term in Eq.(6.20). The acknowledgment overhead therefore will be the time required to transmit only those packets with acknowledgment signals. This time is represented by the second term of Eq.(6.20) as

$$\text{Acknowledgment delay per packet} = [\frac{P(\geq 1, L)}{1 - P(1\geq, L)}] \cdot [A + \frac{L}{R}]$$

Thus the total transmission time for the selective-repeat ARQ system to transmit an image file of size M bits is given by:

$$T_{t2} = (\frac{M}{B}) \cdot [(\frac{L}{R}) + (\frac{P(1\geq, L)}{1 - P(1\geq, L)}) \cdot (A + \frac{L}{R})] \qquad (6.24)$$

The throughput efficiency of an selective-repeat ARQ system is given by [21, 22, 135, 136]:

$$E_2 = (\frac{B}{L}) \cdot (1 - P(1\geq, L)) \qquad (6.25)$$

6.4 Summary

The basic categories of error control techniques used in digital communication systems are presented in this chapter. These are, Forward Error Correcting and Automatic Repeat Request (ARQ) techniques. The application of the error control techniques to mobile channels are considered. For the FEC, an interleaving technique with a random error correcting code was proposed to combat errors due to mobile channels. Three error correcting codes based on the majority-logic decodable codes were proposed and the decoding procedure for each code was presented. For the ARQ, the performance in terms of the transmission time required to transmit an image file and the channel throughput of the stop-and-wait and the selective-repeat techniques was presented. The results, obtained by computer simulation for the proposed three error correcting codes, both using interleaving and using ARQ techniques for protecting the transmitted image data when subjected to errors due to mobile channels, are presented in the following chapter.

CHAPTER 7

TRANSMISSION OF IMAGE DATA TO MOBILE CHANNELS WITH ERROR PROTECTION

7.1 Introduction

In chapter 6, the applications of error control techniques in digital communications were presented. For mobile channels, several error control schemes were proposed to combat transmission errors. In this chapter the performance of the transmitted line diagram test images over mobile channels is evaluated using the proposed error control schemes. In section 7.2 the performance of the proposed forward error correcting (FEC) codes is evaluated using different degrees of interleaving and for different mobile channel conditions. The performance results of the transmitted test images using the selected forward error correcting code with interleaving is given in section 7.3. Section 7.4 deals with the performance evaluation when using automatic repeat request techniques (ARQ). Finally, a summary is given in section 7.5.

7.2 Evaluation of the Proposed FEC Codes with Interleaving Under Different Mobile Channel Conditions

In this section the performance of the proposed error correcting codes is evaluated by computer simulation using various interleaving degrees under different mobile channel conditions. The code with interleaving which shows comparatively good performance results is then used for protecting the transmitted image file data. The evaluation is carried out using a combination of the proposed error correcting codes with various interleaving degrees and under different mobile channel conditions [117]. Throughout the evaluation the various parameters taken into consideration are:

a- Error Correcting Codes:

Three random error correcting codes based on the majority-logic decodable codes were proposed to combat transmission errors in mobile channels (see chapter 6). These codes are: (7, 4, 1), (15, 7, 2) and (73, 45, 4) with code rates of 0.57, 0.47 and 0.61 respectively.

b- Interleaving Degree:

Different Interleaving degrees up to 200 bits were used. For comparison, the performance with no interleaving was also evaluated.

c- Mobile Channel Parameters:

A total of 12 error files generated by channel modelling (see chapter 4) were used. Each error file represents the condition of a mobile channel at certain parameters. For error files 1 to 4, 5 to 8 and 9 to 12 the corresponding average BERs are around 0.0005, 0.005 and 0.017 respectively.

The procedure of the evaluation is carried out by computer simulation and is described as follows. In order to investigate and analyse the number of errors in the data digits before and after decoding we considered the source data of the test image 1 (3507 bits) as an example of the transmitted source data. The source data of the test image 1 was encoded using each of the three error correcting codes (7, 4, 1), (15, 7, 2) and (73, 45, 4). In the encoding operation, the information data block k digits are encoded in the corresponding block encoder into n bits by computing the redundancy symbol values m = n-k bits. The codewords are in systematic form with the first m components of the code equal to redundancy bits and the last k components equal to the information bits. The encoded data codewords were then ready for transmission, assuming no interleaving was to be implemented.

The encoded source data was also interleaved to different degrees. The next step was to find the effect of mobile transmission errors on the interleaved image data codewords. For this purpose, a total of 12 error files were used which cover most practical conditions of mobile channels. For a certain error file, a random position within the error file was selected and the encoded image data was added in modulo-2 sum to the content of the error file from the randomly selected position of the error file up to the end of the encoded image data. The result of the sum data represents the encoded image data affected by mobile transmission errors. The number of errors in the randomly chosen period of the error file represents the error-rate in the encoded data or the channel bit error-rate BER before decoding.

At the receiver terminal, the received data was first de-interleaved in the case of interleaving and then decoded according to the majority-logic decodable procedure as described in chapter 6. To obtain the number of errors in the data codewords after decoding, the decoded data codewords were added in modulo-2 sum to the original encoded data codewords of the test image 1. The number of binary 1s from the modulo-2 adder represents the number of errors in the received data of the test image 1 after decoding. The number of errors after decoding indicates the bit error-rate BER after decoding (including error corrections with various degree of interleaving). In the simulation process, the decoding attempted to correct errors in the received codeword based on the computed syndrome. If the errors are uniformly distributed in the received image file data so that the occurrence of errors beyond the capability limit of the error correcting code used is rare, then the probability that all errors will be corrected in the received image file data is quite high. However, if the errors are distributed in such a manner that a large number of codewords have errors greater than the capability limit of the error correcting code used, then the number of errors after decoding may still be significant. In such a case it is even possible that the decoded codewords will contain a number of errors larger than the input errors before decoding. A large number of computer runs were conducted to cover most periods of the error file and to obtain reliable figures for the performance evaluation.

To investigate and compare the performance results of the implemented error correction codes, an improvement factor gained by coding was calculated. The improvement factor is defined as the ratio of the BER in the encoded data before decoding to the BER after decoding [132, 133]. A block diagram of a program for simulating the performance of the proposed binary cyclic majority-logic decodable codes is shown in Fig. 7.1.

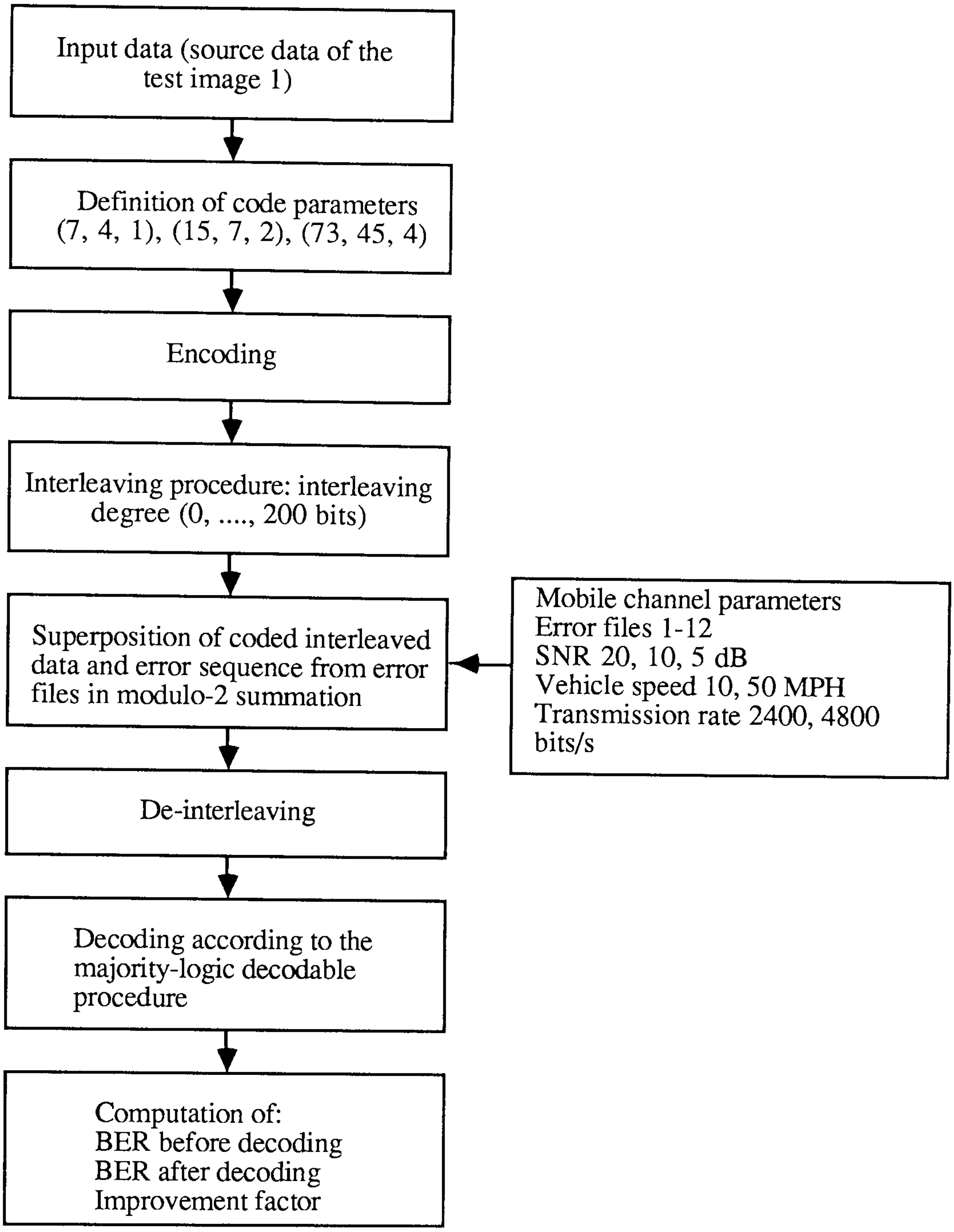


Fig. 7.1 Block diagram of a program for simulating the performance of the proposed forward error correcting codes using interleaving under different mobile channel conditions.

Evaluation Results without Interleaving

The performance of the proposed error correcting codes was first evaluated without interleaving under different mobile channel conditions. The performance of the proposed codes implemented over a channel with random errors and with an average BER value the same as for the mobile channel was also evaluated. In this manner, it will be possible to investigate and compare the performance of the proposed error correcting codes when used without interleaving over mobile and random channels. The results of the evaluation for the codes (7, 4, 1), (15, 7, 2) and (73, 45, 4) are shown in Table 7.1.

In comparing the performance results of the proposed error correcting codes implemented over a mobile channel at a relatively low value of BER of around 0.0005 which is the case of error files 1 to 4, it will be seen that a noticeable coding improvement is observed using certain error files, where short error bursts or randomly errors are predominantly obtained. Under such conditions, the comparatively long codeword (73, 45, 4) performed best when using error files 2 and 4 which correspond to the mobile channels at high vehicle speed. However, for the same channel BER and at low vehicle speed conditions, a negligible improvement is obtained due to the occurring of relatively long error bursts. At a relatively higher value of BER of around 0.005 which is the case of error files 5 to 8, it can be seen that a negligible coding improvement is obtained for all the proposed codes.

At a high value of BER of around 0.017, which is the case of error files 9 to 12, it will be seen that almost there is no improvement in coding. In fact for a relatively long codeword such as the code (74 ,45, 4) the average values of BER after decoding are higher. This is because of the relatively long length of the codeword and the frequent occurring of long error bursts at high values of BER. This results in a high probability that a long codeword would contain more errors than its error correcting capability limit. In such conditions the number of errors in a codeword after decoding is higher than

Table 7.1 Performance results of the proposed error correcting codes without interleaving under different mobile channel conditions (see page 87).

Error file			Error-rate before decoding	Code 1 (7, 4, 1)		Code 2 (15, 7, 2)		Code 3 (73, 45, 4)	
				Error-rate after decoding	Improv. factor	Error-rate after decoding	Improv. factor	Error-rate after decoding	Improv. factor
No.	R	V							
1	2.4	10	5×10^{-4}	3.8×10^{-4}	1.31	3.29×10^{-4}	1.52	2.6×10^{-4}	1.92
2	2.4	50	=	1.3×10^{-4}	3.84	3.7×10^{-5}	13.5	5.1×10^{-7}	980
3	4.8	10	=	4×10^{-4}	1.25	4×10^{-4}	1.25	4.4×10^{-4}	1.13
4	4.8	50	=	2.8×10^{-4}	1.78	1.6×10^{-4}	3.125	3.7×10^{-5}	13.5
5	2.4	10	5×10^{-3}	4.3×10^{-3}	1.16	4.3×10^{-3}	1.16	4.94×10^{-3}	1.01
6	2.4	50	=	3.65×10^{-3}	1.37	2.78×10^{-3}	1.8	1.89×10^{-3}	2.64
7	4.8	10	=	4.2×10^{-3}	1.19	4.25×10^{-3}	1.17	4.95×10^{-3}	1.01
8	4.8	50	=	3.9×10^{-3}	1.28	3.53×10^{-3}	1.41	3.44×10^{-3}	1.45
9	2.4	10	1.7×10^{-2}	1.57×10^{-2}	1.08	1.6×10^{-2}	1.06	1.89×10^{-2}	0.9
10	2.4	50	=	1.5×10^{-2}	1.13	1.4×10^{-2}	1.21	1.5×10^{-2}	1.13
11	4.8	10	=	1.64×10^{-2}	1.03	1.6×10^{-2}	1.06	1.9×10^{-2}	0.89
12	4.8	50	=	1.56×10^{-2}	1.09	1.54×10^{-2}	1.1	1.8×10^{-2}	0.94
Random Errors			5×10^{-4}	4.3×10^{-6}	116	2×10^{-7}	2.5×10^{3}	1×10^{-7}	5×10^{3}
Random Errors			5×10^{-3}	1.9×10^{-4}	26.3	7.2×10^{-6}	694	4.1×10^{-6}	1220
Random Errors			1.7×10^{-2}	2.49×10^{-3}	6.82	4.86×10^{-4}	34.98	9.46×10^{-4}	17.97

before decoding and therefore the value of the improvement factor becomes less than 1.

As a summary, it can be said that the performance of the proposed random error correcting codes is poor, as expected, when implemented over mobile channels, even at relatively low bit error-rates. This result can also be justified when comparing the performance of the proposed error correcting codes implemented over a channel with random errors. It can be seen from Table 7.1 that for a certain BER the performance results of the proposed error correcting codes over a random channel are much better than that used without interleaving over a mobile channel. It is therefore, essential to use interleaving techniques to randomize the burst error patterns and then use random error correction codes.

Evaluation Results with Interleaving

In this section the performance evaluation of the error correcting codes, implemented by computer simulation, is examined using a combination of selected interleaving degrees under different mobile channel conditions. The results of the performance evaluation are given in the form of graphs. In each graph, the average values of the BER after decoding for the three error correcting codes are plotted versus interleaving degrees for certain mobile channel conditions which correspond to a specific error file. In each graph the proposed codes are; code 1 (7, 4, 1), code 2 (15, 7, 2) and code 3 (73, 45, 4).

The results of the performance evaluation can be classified according to error files which have similar values of BER . For error files 1 to 4 of low values of BER around 0.0005, it is to be expected that using a small amount of interleaving would give good results. It was shown that at such low BER the long codeword (73, 45, 4) without interleaving performed best using error files 2 and 4 which contain comparatively short error bursts. We shall consider therefore the effect of interleaving using error files which contain longer error bursts. This is because interleaved codewords that give good performance using a bursty error file will give almost similar or even better performance using error files of shorter error bursts. Error file 3 (SNR = 20 dB, vehicle speed = 10 MPH, transmission rate = 4800 bits/s) which contains comparatively longer error bursts than error files 1, 2, and 4 was therefore considered.

Fig. 7.2 shows the performance evaluation of the three proposed error correcting codes with interleaving, as implemented by computer simulation, using the error file 3 of BER around 0.0005. From this figure it can be seen that the average BER after decoding of the proposed codes decreases significantly with increasing interleaving degree indicating that the channel has been almost transformed into a random channel. In comparison, the long codeword (73, 45, 4) performs best, where at an interleaving degree of about 10 bits or higher the average BER after decoding approaches almost zero (improvement factor near to infinity). At an interleaving degree about 20 bits or higher, the codeword (15, 7, 2) shows the same performance as the long codeword.

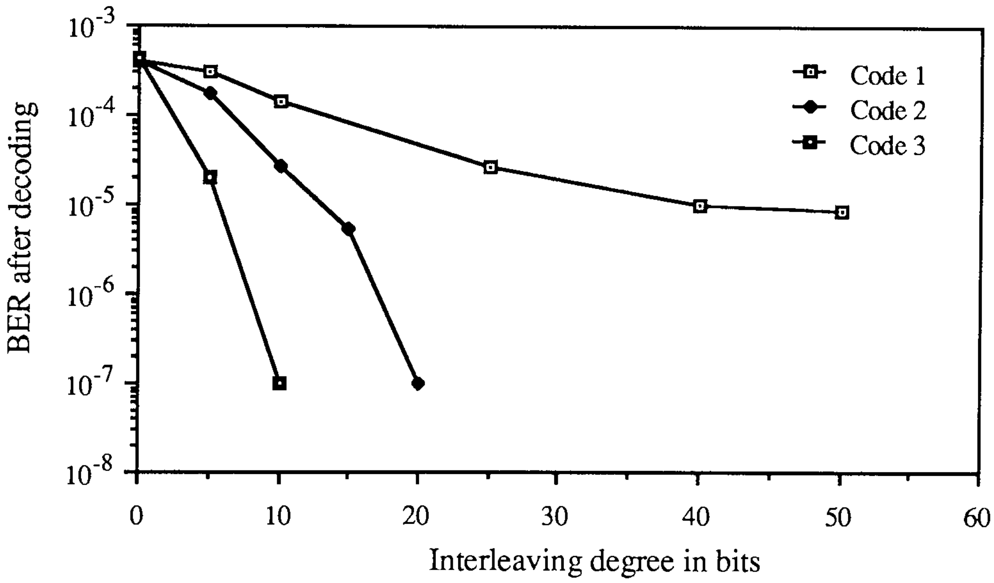


Fig. 7.2 Performance results of the proposed error correcting codes with interleaving using error file 3.

At such interleaving degrees, both codes can be used very efficiently to protect the transmitted test images using error files 1 to 4. For the code (7, 4, 1), the BER levels off at interleaving degree about 40 bits, at which an improvement factor = 4.8x10^{-4} / 1.03x10^{-5} = 46 is obtained.

The performance of the three error correcting codes is now examined using a combination of the selected interleaving degrees and error files 5 to 8 of higher values of BER around 0.005. For such BER we use error files 5 and 7, which represent a mobile channel at low vehicle speed, and thus contain error bursts of longer lengths than error files 6 and 8 at high vehicle speed. The results of the average BER for the three error correcting codes against interleaving degrees using error files 5 and 7 which represent the mobile channel at a SNR 10 dB, a vehicle speed 10 MPH and transmission rates of 2400 bits/s and 4800 bits/s are shown in Figures 7.3 and 7.4 respectively. It can be seen that interleaving leads to a noticeable improvement in the coding performance. Here again the performance of the comparatively long codeword (73, 45, 4) shows better performance for the same interleaving degree.

From Fig. 7.3, which corresponds to the error file 5, it can be observed that at interleaving degrees of about 30 and 60 bits the average BER after decoding for the codes (73, 45, 4), (15, 7, 2) and (7, 4, 1) levels off at 6x10^{-6} (improvement factor = 4.9x10^{-3} / 6x10^{-6} = 816), 1.6 x10^{-5} (improvement factor = 4.75x10^{-3} / 1.6x10^{-5} = 290) and 2.38x10^{-4} (improvement factor = 4.7x10^{-3} /2.38x10^{-4} = 19.7) respectively. In Fig.7.4, which corresponds to the error file 7, it can be seen that a larger value of interleaving degree is required to level off the BER than that used for the error file 5. At interleaving degrees of about 50 bits and 100 bits, the average BER after decoding for the codes (73, 45, 4), (15, 7, 2) and (7, 4, 1) levels off at 6.6x10^{-6} (improvement factor = 4.8x10^{-3} / 6.6x10^{-6} = 727), 2.1x10^{-5} (improvement factor = 4.94x10^{-3} / 2.12x10^{-5} = 232) and 3.29x10^{-4} (improvement factor = 5.05x10^{-3} / 3.29x10^{-4} = 15.3) respectively.

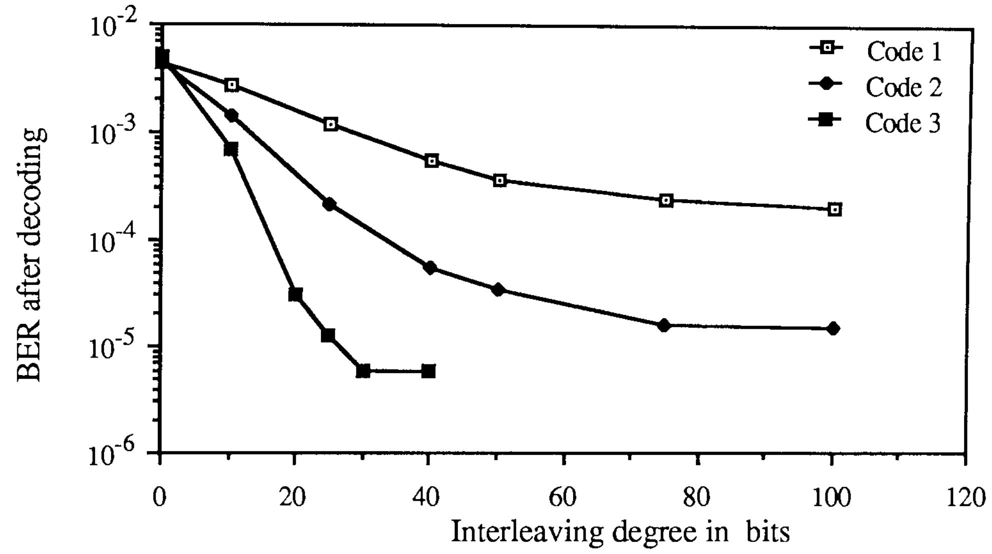


Fig. 7.3 Performance results of the proposed error correcting codes with interleaving using error file 5.

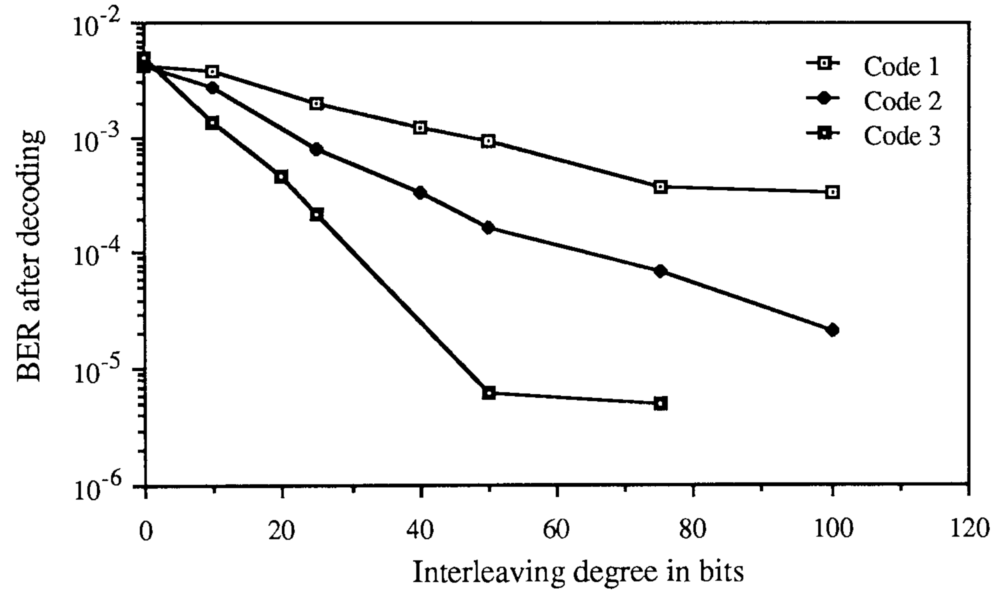


Fig. 7.4 Performance results of the proposed error correcting codes with interleaving using error file 7.

Finally, the performance of the three error correcting codes is examined using a combination of the selected interleaving degrees and the error files 9 to 12 at higher values of BER around 0.017. This value of BER is considered to be high and, therefore, it would be helpful to show the effect of interleaving using all error files 9 to 12. Figures 7.5, 7.6, 7.7 and 7.8 show the performance of the three error correcting codes for various interleaving degree using error files 9 to 12 respectively.

It was shown above that, for a mobile channel of BER around 0.005 or less (error files 1 to 8), the long codeword (73, 45, 4) performed best. However, it can be seen from Figures 7.5 to 7.8 that, at a high channel BER around 0.017, the codeword (15, 7, 2) gives the best performance results for all error files 9 to 12. This is because at a high value of channel BER, the probability that the long codeword (73, 45, 4) would contain more errors than its error correction capability limit is high, and therefore its performance degrades at high channel BER. For the error files 9 and 11 (Fig. 7.5 and 7.7), which represent the mobile channels at a SNR of 5 dB, a vehicle speed of 10 MPH and transmission rates of 2400 bits/s and 4800 bits/s respectively, it can be seen that interleaving degrees of about 100 bits and 200 bits are required to level off the values of the BER after decoding. The reason why the error file 11 requires longer interleaving degree is because the error bursts at 4800 bits/s will last typically for twice as many bits as at 2400 bits/s (see chapter 4), and, therefore, an interleaving degree of about twice as many bits will be required to achieve an equivalent degree of error dispersion. For the error files 10 and 12 at higher vehicle speed of 50 MPH (Figures 7.6 and 7.8), it can be seen that interleaving degrees of about 25 bits and 50 bits are required to start the level off of the BER.

Considering the error file 11 (Fig. 7.7), which contains the longest error bursts among the simulated error files, it can be observed that at interleaving degree of 200 bits the average BERs after decoding for the three codes level off at about the following values:

code 1 (7, 4, 1); at 0.00316 (improvement factor = 0.0174 / 0.00316 = 5.5)

code 2 (15, 7, 2); at 0.00058 (improvement factor = 0.0171 / 0.00058 = 29.48)

code 3 (73, 45, 4); at 0.00123 (improvement factor = 0.0175 / 0.00123 = 14.2)

At the same interleaving degree of 200 bits the values of the BER after decoding using error files 9, 10 and 12 (Figures 7.5, 7.6, 7.8) are smaller. Therefore, using code 2 (15, 7, 2) with interleaving degree of 200 bits, an average BER after decoding of 0.00058 or less will be obtained for error files 9 to 12.

The interleaving degree gives an indication of the length of the error burst that can be handled. It was shown in chapter 4 that 90% of error bursts obtained in the error file 11 were shorter than 125 bits and error bursts of lengths up to 290 bits also occurred but with very small probability. It is to be expected, therefore, that the interleaving degree of 200 bits will be adequate to tolerate the majority of long error bursts.

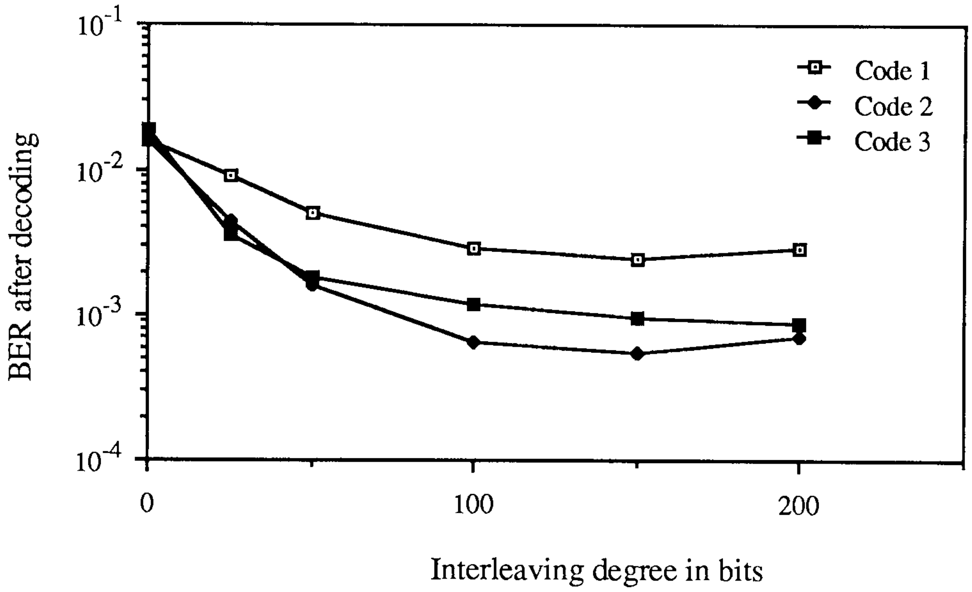


Fig. 7.5 Performance results of the proposed error correcting codes with interleaving using error file 9.

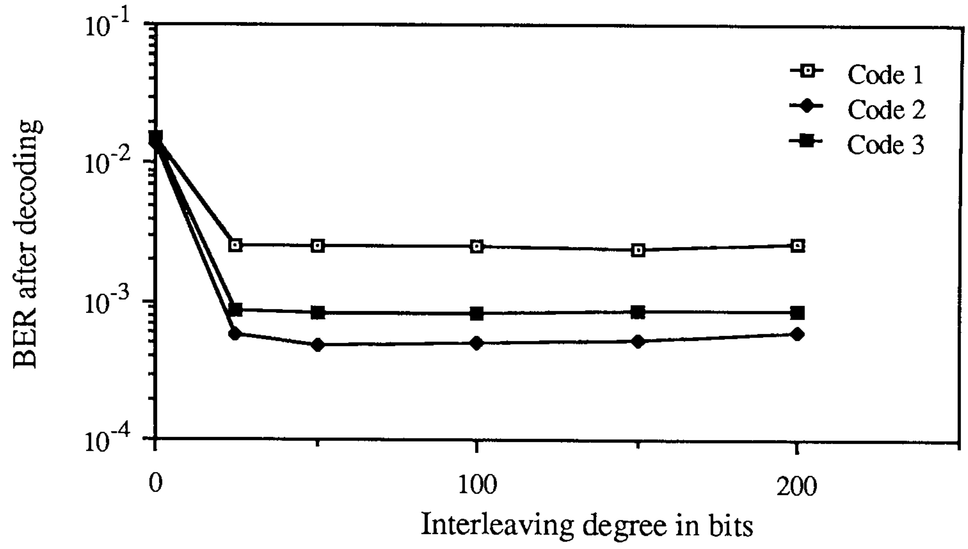


Fig. 7.6 Performance results of the proposed error correcting codes with interleaving using error file 10.

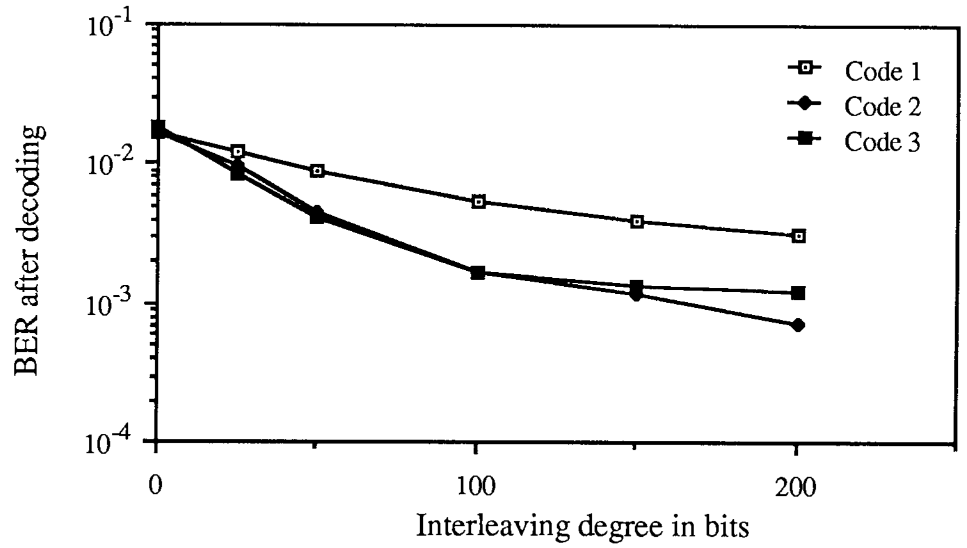


Fig. 7.7 Performance results of the proposed error correcting codes with interleaving using error file 11.

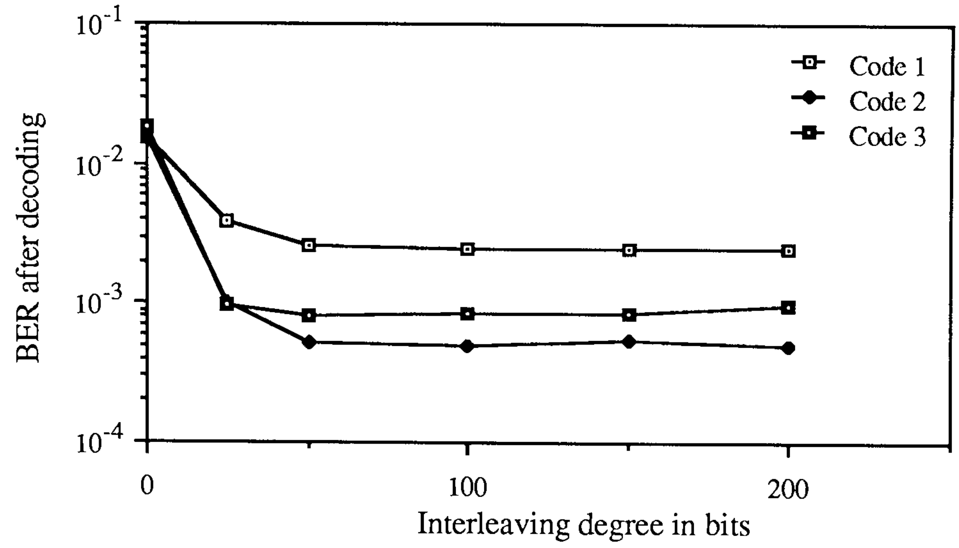


Fig. 7.8 Performance results of the proposed error correcting codes with interleaving using error file 12.

Summary of the Performance of the Proposed Error Correcting Codes with Interleaving:

It has been shown that in mobile channels the combination of interleaving and error correction codes provides significantly better performance in error correction than error correction coding alone. In addition, the improvement of the performance was shown to be directly related to the effective randomization achieved by the interleaving procedure. The summary of the performance evaluation for the proposed error correcting codes (7, 4, 1), (15, 7, 2) and (73, 45, 4) simulated by computer is given as follows [117];

a) For all error files 1 to 12, code 3 (73, 45, 4) and code 2 (15, 7, 2) show better performance than code 1 (7, 4, 1).

b) For error files 1 to 4 with low values of BER around 0.0005, the relatively long codeword (73, 45, 4) performed best when interleaved to about 10 bits or higher.

At such conditions the average BER after decoding approaches almost zero. At an interleaving degree of about 20 bits or higher the code (15, 7, 2) shows as good a performance as the code (73, 45,4).

c) For error files 5 to 8 with values of BER around 0.005, the code (73, 45, 4) also shows the best performance with an interleaving degree about 40-50 bits. Here again the code (15, 7, 2) shows as good a performance as the long codeword with an interleaving degree about 100 bits.

d) In the case of error files 9 to 12 of higher values of BER around 0.017, the performance of the code (15, 7, 2) shows an improvement in comparison to the (73, 45,4) using same interleaving degree.

e) The interleaving procedure means storage requirement and time delay. For this reason the interleaving degree should be chosen as small as possible. Assuming the same degree of interleaving is used, the storage size of the interleaving matrix required for the code (15, 7, 2) at the transmitter and receiver is about 73 / 15 = 4.8 times less than the storage required for the code (73, 45, 4). The same factor applied also to the system delay caused by the interleaving procedure at both the transmitter and receiver.

f) With respect to both the encoding and decoding procedure and complexity, it is obvious that the longer the codeword will be, the more complex and time consuming the encoding and decoding operation. In this category the code (15, 7, 2) is preferable to the long code (73, 45,4).

From the above summary it was decided to use the code (15, 7, 2) with different values of interleaving degrees for protecting the transmitted image data. The degrees of interleaving were assumed to be selectable at the transmitter, depending on the mobile channel conditions. For mobile channels of low BER around 0.0005 (error files 1 to 4), an interleaving degree of 20 bits was used. At higher channel BER about 0.005 (error files 5 to 8) an interleaving degree of 100 bits was used, and finally for bad channel conditions, channel BER about 0.017 (error files 9 to 12), an interleaving degree of 200 bits was used. In practical situations, the procedure for selecting the interleaving degree will depend on the design structure of the transmitter and the receiver. In this study we assume that it is possible to use a selected level of interleaving. It is also possible to use a fixed interleaving degree, in which case the largest interleaving degree should be selected under various mobile channel conditions. This situation has the drawback that it requires a comparatively longer system delay during the better conditions of the mobile channels. However, it has the advantage that it does not require any additional structure to change the level of interleaving at the transmitter and receiver.

We now proceed to calculate the throughput efficiency of the (15, 7, 2) FEC code and the transmission time required to transmit the test images 1 and 2 when encoded with the (15, 7, 2) code. The throughput efficiency is defined as the ratio of the number of the information binary digits transmitted to the total number of binary digits transmitted. The throughput efficiency for the forward error correcting codes is constant and is equal to the code rate. For the (15, 7, 2) code the throughput efficiency = 7 / 15 = 0.466

In forward error correcting schemes the transmission time (T_f) required to transmit a data file is constant, independent on the transmission errors, and is given by:

$$T_f = \frac{\text{Data file size}}{\text{Transmission rate}} \text{ x } \frac{1}{\text{Code rate}}$$

At a transmission rate of 2400 bits/s, the transmission time required for the test image 1 (T_{f1}) of file size 3507 bits is given by:

$$T_{f1} = \frac{3507}{2400} \text{ x } \frac{15}{7} = 3.13 \text{ seconds}$$

The transmission time required for the test image 2 (T_{f2}) of file size 7595 bits using the same transmission rate is 6.77 seconds.

7.3 Performance Results of the Transmitted Test Images Using FEC and Interleaving

In this section the performance of the transmitted line diagram test images is evaluated using the (15, 7, 2) forward error correcting code with three values of interleaving degrees of 20, 100 and 200 bits respectively. The performance of the received test images is evaluated subjectively. The procedure used for the subjective evaluation is similar to that given in chapter 5. The results of the subjective performance tests for the test images 1 and 2 are presented for different mobile channel conditions such as SNR (20, 10, and 5 dB), transmission rate (2400 and 4800 bits/s), vehicle speed (10 and 50 MPH). Error files 1 to 12 were used to represent the above channel conditions. A number of transmission tests were carried out for each test image and error file. In each test, a random position within the error file was selected. The image file data was encoded with the forward error correcting code (15, 7, 2), interleaved and added to the content of the error file from the randomly selected position of the error file up to the end of the encoded image data file. The result was the transmitted image file data corrupted with mobile channel errors. At the receiver the data was first de-interleaved and then decoded according to the majority-logic decodable procedure (see chapter 6). The image file data after decoding was then interpreted and processed using the receiver protocol developed in chapter 5 (section 5.2.3). The reproduced images were recorded in the form of computer plots ready for subjective tests.

Performance Results using Error Files 1-4

In this section the performance results of the test images 1 and 2 are presented, when encoded with the (15, 7, 2) FEC code and interleaved to 20 bits. The results are given when subjecting the test images to mobile transmission errors which are represented by error files 1-4, SNR of 20 dB, transmission rate (2400 and 4800 bits/s) and vehicle speed (10 and 50 MPH) with channel BER of about 0.0005. Several transmission tests were conducted for test images 1 and 2 under the above conditions and it was found that for all the tests the reproduced test images were 100 % without errors. This means that all the received test images were graded 5 when using the 5-point subjective assessment grade scale. In comparing the performance results of the transmitted test images without error correction and interleaving as shown in chapter 5 (Tables 5.3 to 5.6), it will be seen that the maximum and minimum percentage of the test images 1 and 2 received without errors were 75.8% , 55 % (maximum) and 43 %, 20 % (minimum) respectively (Table 5.5 and 5.4). In comparison, it can be seen that a significant improvement is obtained in the case of encoding and interleaving, since 100% of the test images 1 and 2 were received without errors.

Performance Results using Error Files 5-8

In this section the performance results of the test images 1 and 2 encoded with the (15, 7, 2) FEC code and with 100 bits interleaving degree are presented. The results are shown when subjecting the test images to mobile transmission errors which are represented by error files 5-8, SNR of 10 dB, transmission rate (2400 and 4800 bits/s) and vehicle speed (10 and 50 MPH) with channel BER of about 0.005. Several transmission tests were conducted for the test images 1 and 2 under the above conditions. The results of transmission tests show that a large number of the reproduced test images were received without errors. Table 7.2 shows the percentage of the test images received without errors for error files 5 to 8. It can be seen that 98.15% and 96.4 % or higher of the test images 1 and 2 are received without errors, for error files 5 to 8 (i.e., graded 5 in the 5-point subjective assessment grade scale). In comparing the performance results shown in Table 7.2 with the results of the transmitted test images without error correction and interleaving as shown in chapter 5 (Tables 5.7 to 5.10), it will be seen that a considerable improvement is obtained when using FEC and interleaving. In the case of the unprotected test images (Tables 5.7 to 5.10) the maximum percentage of the test images received without errors was only 13.6% and 4.7 % for the test images 1 and 2

(Table 5.9) compared to 98.15 and 96.4 for the protected test images 1 and 2 for the same channel conditions (Table 7.2).

Table 7.2 Percentage of the test images 1 and 2 received without errors using forward error correcting code and interleaving for error files 5-8

Error File (Error rate = 0.005) No. Rate Speed	Percentage of test image 1 received without error	Percentage of test image 2 received without error
5 2.4 10	99.45	98.3
6 2.4 50	98.9	97.4
7 4.8 10	98.15	96.4
8 4.8 50	99.2	98.1

Performance Results using Error Files 9-12

The performance results of the test images 1 and 2 encoded with the (15, 7, 2) FEC code and interleaved with 200 bits are now presented. The results are shown when subjecting the test images to mobile transmission errors which are represented by error files 9-12, SNR of 5 dB, transmission rate (2400 and 4800 bits/s) and vehicle speed (10 and 50 MPH) with channel BER of about 0.017. It is expected that at such high values of channel BER the performance results degrade in comparison to the results of error files 1-8. The performance results for such channel conditions are given in Tables 7.3 to 7.7. Tables 7.3 and 7.4 show the survey results of the performance analysis for a mobile channel of SNR 5 dB, transmission rate 2400 bits/s and two vehicle speeds (low speed of

10 MPH and high speed of 50 MPH) (error files 9 and 10). Tables 7.5 and 7.6 show the survey results when the transmission is increased to 4800 bits/s (error files 11 and 12). Table 7.7 shows the results of the average number of erroneous shapes in the test images 1 and 2 for error files 9 to 12.

It can be seen that the average grade values for the quality and usefulness subjective test analysis are usually higher than 4 for different mobile channel conditions which are represented by error files 9 to 12. In general, these figures were considered good and acceptable by the observers.

For Tables 7.3 to 7.6 the average channel BER, BER after decoding and the improvement factor obtained after decoding are as follows;

Table 7.3, error file 9;

Average channel BER = 0.0168, Average BER after decoding = 0.000455, Improvement factor = 0.0168 / 0.000455 = 36.9.

Table 7.4, error file 10;

Average channel BER = 0.017, Average BER after decoding = 0.00057, Improvement factor = 0.017 / 0.00057 = 29.8.

Table 7.5, error file 11;

Average channel BER = 0.0171, Average BER after decoding = 0.00058, Improvement factor = 0.0171 / 0.00058 = 29.48.

Table 7.6, error file 12;

Average channel BER = 0.0168, Average BER after decoding = 0.000505, Improvement factor = 0.0168 / 0.000505 = 33.26.

From Tables 7.3 to 7.7 it can be seen that the results of the subjective performance tests for the test image 1 are better than for the test image 2. This is because the size of the test image 1 is smaller than for the test image 2 and also the shape of the test image 1 was visually more predictable in comparison to the test image 2. Accordingly, the effect of errors was considered to be more serious on the test image 2.

In comparing the results of Tables 7.3 to 7.6 it can be seen that the results in Table 7.5 (SNR = 5 dB, vehicle speed = 10 MPH, transmission rate = 4800 bits/s) show the best subjective performance. This result is obtained although the improvement factor obtained from interleaving and decoding for the Table 7.5 is the lowest. The reason for this is as follows. At a low vehicle speed and high transmission rate the average number of bits that occur in both the nonfade and fade periods over the mobile channel are the largest in comparison to other channel conditions. For this reason it is to be expected that the improvement obtained due to interleaving and error correction procedure is comparatively small. The decoding tends to correct all types of short burst errors or random errors. However, in some situations, the error correcting procedure fails to correct transmission errors. For example, when two or more long burst errors occur within short time intervals. The effect of such a case is that several codes usually occur in series containing errors after decoding. It was shown that the data format of a drawing element within the image file data consists of several code bytes followed by a data format of the next drawing element. Thus it is expected that the erroneous codes which occur in series will be the data format of one or two drawing elements in series, depending upon the length of the drawing elements and the number of erroneous codes.

For other channel conditions (Tables 7.3, 7.4 and 7.6) it can be seen that the improvement obtained due to interleaving and decoding is higher because of relatively short burst errors. However, the results of the subjective performance tests are relatively lower in comparison to Table 7.5. This is because, although the number of erroneous codes were smaller, they usually occur randomly in comparison to the case of the Table 7.5 and, as a result, they affect more drawing elements within the image file. For this reason the results shown in Table 7.4 (SNR = 5 dB, vehicle speed = 50 MPH, transmission rate = 2400 bits/s) shows comparatively the lowest performance.

From Tables 7.3 to 7.6 it can seen that the average BER after decoding ranges from 0.00045 to 0.00058. These values are similar to the case of the mobile channel conditions which are represented by error files 1 to 4, with a channel BER around 0.0005. In chapter 5 the performance of the unprotected test images 1 and 2 were evaluated using error files 1 to 4 (see chapter 5, section 5.3, Tables 5.3 to 5.6). In comparing the results of Tables 7.3 to 7.6 with the results shown in Tables 5.3 to 5.6, it can be seen that a slightly better performance is obtained in Tables 7. 3 to 7.6. This result is obtained although the average values of BER after decoding in Tables 7.4, 7.5 and 7.6 are slightly higher than those used in Tables 5.3 to 5.6. The reason for this is that in the case of unprotected image data the transmission errors consist of short burst errors and random errors which cause erroneous drawing elements according to the occurrence of the errors. In the case of the protected image data with FEC and interleaving and with high channel BER, the data format after decoding contains comparatively less random or short errors and hence less drawing elements were affected. Because erroneous codewords after error correction usually occur in groups or bursts, they affect many codes within a drawing element. The subjective test results of such a case is very similar to when a smaller number of codes within a drawing element are affected and, as a result, better performance results are obtained (see chapter 5, section 5.3).

Table 7.3 Subjective performance analysis using forward error correcting code and interleaving at SNR = 5 dB, transmission rate = 2400 bits/s, vehicle speed = 10 MPH (error file 9)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	78.6	64.2	78.25	57.4
Grade 4	10.5	17.1	5.08	20.6
Grade 3	7.5	12.2	9.16	12.4
Grade 2	3.3	4.5	6.66	6.6
Grade 1	0	2	0.83	3
Average grade	4.64	4.37	4.53	4.22

Table 7.4 Subjective performance analysis using forward error correcting code and interleaving at SNR = 5 dB, transmission rate = 2400 bits/s, vehicle speed = 50 MPH (error file =10)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	61.6	42.4	60.9	48.3
Grade 4	20.2	26.5	24.2	24.1
Grade 3	6.1	11.7	10.2	17.2
Grade 2	8.3	14.1	2.8	6.9
Grade 1	3.7	5.2	1.8	3.4
Average grade	4.27	3.86	4.39	4.07

Table 7.5 Subjective performance analysis using forward error correcting code and interleaving at SNR = 5 dB, transmission rate = 4800 bits/s, vehicle speed = 10 MPH (error file 11)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	83.5	75.7	78.7	62.4
Grade 4	10.3	14.3	13.8	22.5
Grade 3	3.7	4.8	2.5	8.8
Grade 2	1.3	3.1	3.7	2.1
Grade 1	1.2	2.1	1.2	4.2
Average grade	4.73	4.58	4.65	4.36

Table 7.6 Subjective performance analysis using forward error correcting code and interleaving at SNR = 5 dB, transmission rate = 4800 bits/s, vehicle speed = 50 MPH (error file 12)

Five-point grade scale	Quality analysis		Usefulness analysis	
	% Test Image 1	% Test Image 2	% Test Image 1	% Test Image 2
Grade 5	68.3	54.2	64.7	50.6
Grade 4	14.7	20.0	22.8	41.3
Grade 3	8.5	15.3	8.7	4.8
Grade 2	3.8	7.3	2.8	0.0
Grade 1	4.7	3.2	1.0	3.2
Average grade	4.38	3.98	4.47	4.2

Table 7.7 Average number of erroneous elements in the test images 1 and 2 using forward error correcting code and interleaving for error files 9 to 12

Error File (Error rate = 0.017) No.	Rate	Speed	Average erroneous elements in image 1	Average erroneous elements in image 2
9	2.4	10	0.42 = 0.73 %	0.98 = 1.07 %
10	2.4	50	0.66 = 1.15 %	1.44 = 1.58 %
11	4.8	10	0.37 = 0.65 %	0.91 = 1%
12	4.8	50	0.64 = 1.12 %	1.22 = 1.34 %

7.4 Performance Results of the Transmitted Test Images Using Automatic Repeat Request (ARQ)

In this section automatic repeat request (ARQ) techniques are used to protect the transmitted line diagram test images over mobile channels. In the ARQ techniques, image data stored in the computer file at the transmitter is decomposed into a number of packets. Each packet consists partly of image data and partly of overhead data used for detecting errors that occur in the packet during transmission. Two types of ARQ techniques are used. These are, the stop-and-wait and the selective-repeat techniques. The performance results of the transmitted line diagram images over mobile radio channels are evaluated in terms of the following [105, 117];

1. The transmission time required to transmit the line diagram images without errors over a mobile channel. The evaluation is considered for different packet sizes and different mobile channel parameters.
2. The channel throughput efficiency for different packet size and under different mobile channel conditions.

1. Transmission Time

In chapter 6 the equations related to the transmission time required to transmit test images 1 and 2 over a mobile channel using the stop-and-wait and selective-repeat (ARQ) techniques were presented. In the following, the performance results in terms of the transmission time are presented. The results are shown in Fig. 7.9 to 7.14, where each diagram shows the transmission time as a function of the packet size under a certain mobile channel conditions. The conditions of the mobile channels are represented by error files (see chapter 4). The diagrams show the transmission time required for the test image 1 of file size of 3507 bits. For the test image 2 of file size of 7595 bits the transmission time is proportionally larger and can be obtained from the transmission time of the test image 1 as follows;

$$\text{Transmission time for the test image 2} = \text{Transmission time for the test image 1} \times \left(\frac{7595}{3507}\right)$$

Therefore, similar performance results in terms of transmission time versus packet size are obtained for the test image 2. However, the absolute value of the transmission time is larger by a constant factor.

Figures 7.9 and 7.10 show the performance results in term of the transmission time required to transmit the test image 1 as a function of the packet size for the stop-and-wait and selective-repeat ARQ techniques for error files 1 to 4. Figures 7.11 and 7.12 show the results for error files 5 to 8 and Figures 7.13 and 7.14 show the results for error files 9 to 12.

From Figures 7.9 to 7.14 it can be seen that there is an optimum packet size that gives minimum transmission time for both the stop-and-wait and selective-repeat ARQ techniques. This is because short packets suffer from a proportionately greater number of overhead bits whereas long packets have a low probability of correct transmission [102, 137, 138, 139]. The optimum transmitted packet size at SNR of 20 dB, transmission rate of 2.4 kbits/s and low vehicle speed of 10 MPH (error file 1) are about 575 bits and 425 bits for the stop-and-wait and selective-repeat ARQ (Fig. 7.9). At these values the transmission time required for the test images 1 and 2 are a minimum at 1.85 sec. and 4.01 sec. for the stop-and-wait ARQ and are 1.74 sec. and 3.77 sec. for the selective-repeat ARQ. At high vehicle speed the performance results degrade. This is because the packet error-rate increases at higher speed (see chapter 4). In comparison to Fig. 7.9, the optimum transmitted packet size at SNR of 20 dB, transmission rate of 2.4 kbits/s and high vehicle speed of 50 MPH (error file 2) are reduced to about 375 bits and 300 bits for the stop-and-wait and selective-repeat ARQ (Fig.7.10). At such packet size values the transmission time required for the test images 1 and 2 are increased to 2.05 sec. and 4.4 sec. for the stop-and-wait ARQ and are 1.87 sec. and 4.05 sec. for the selective-repeat ARQ.

The signal to noise ratio is the key factor in the performance. At a SNR of 10 dB the optimum packet size reduces remarkably. In comparison to Fig. 7.9, the optimum transmitted packet size at SNR of 10 dB, transmission rate of 2.4 kbits/s and low vehicle speed of 10 MPH (error file 5) is reduced to about 250 bits for the stop-and-wait ARQ and is about 175 bits for the selective-repeat ARQ (Fig. 7.11) [137]. Under such conditions the transmission time required for the test images 1 and 2 are increased to 2.51 sec. and 5.42 sec. for the stop-and-wait ARQ and are 2.2 sec. and 4.72 sec. for the selective-repeat ARQ. At a vehicle speed of 50 MPH and the other channels parameters the same, the performance results degrade as shown in Fig. 7.12. At such conditions the optimum packet sizes for the stop-and-wait ARQ and the selective-repeat ARQ are about 150 and 125 bits. The transmission times for the test images 1 and 2 are increased to 3.38 and 7.33 seconds for the stop-and wait ARQ and 2.75 and 6 seconds for the selective-repeat ARQ.

At SNR of 5 dB the performance degrades further more. For example, at SNR of 5 dB, transmission rate of 2400 bits/s and low vehicle speed of 10 MPH (error file 9), the optimum packet size is about 175 bits for the stop-and-wait ARQ and is about 125 bits for the selective-repeat ARQ (Fig. 7.13). At such values the transmission time required for the test images 1 and 2 are 3.33 sec. and 7.2 sec. for the stop-and-wait ARQ and are 2.74 sec. and 5.93 sec. for the selective-repeat ARQ. At high vehicle speed of 50 MPH and the other channel conditions the same (error file 10), the performance degrades considerably. At such conditions the optimum packet size is about 100 bits for both the stop-and-wait ARQ and the selective-repeat ARQ (Fig. 7.14). At such packet sizes, the transmission time for the test images 1 and 2 are are 5.25 sec. and 11.38 sec. for the stop-and-wait ARQ and are 4.0 sec. and 8.6 sec. for the selective-repeat ARQ

By comparing the performance results given in Figures 7.9 to 7.14 it can be seen that higher transmission rate as far as the channel allows gives better performance. For example, the results at transmission rate of 4.8 kbits/s shows better performance (shorter transmission time and longer packet size) than the transmission rate of 2.4 kbits/s [137]. This is because for a certain packet size the probability of the packet error rate is lower at higher transmission. Moreover the transmission time is inversely proportional to the transmission rate. The comparisons also show that at high SNR, high transmission rate or low vehicle speed, the transmission time is low and exhibits minor changes around the optimal packet size. However, at lower SNR, higher vehicle speed or lower transmission rate, the transmission time is higher and degrades rapidly around the optimal packet size. Furthermore, the performance results of the ARQ techniques show that the selective-repeat ARQ scheme always gives an improvement factor greater than the stop-and-wait scheme [21, 22].

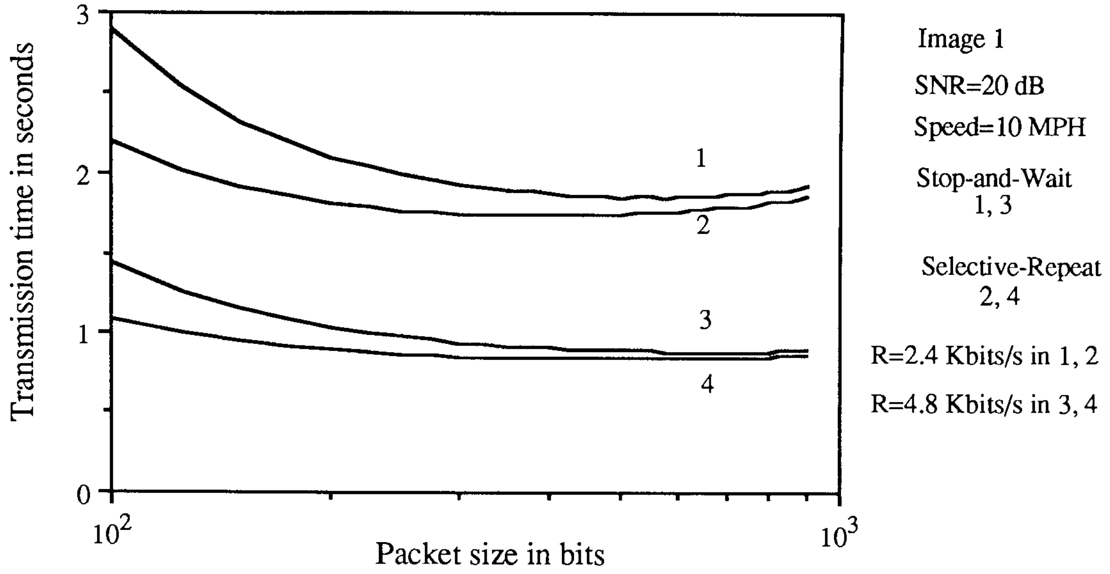


Fig. 7.9 Transmission time for the test image 1 versus packet size using ARQ techniques (error file 1 and 3).

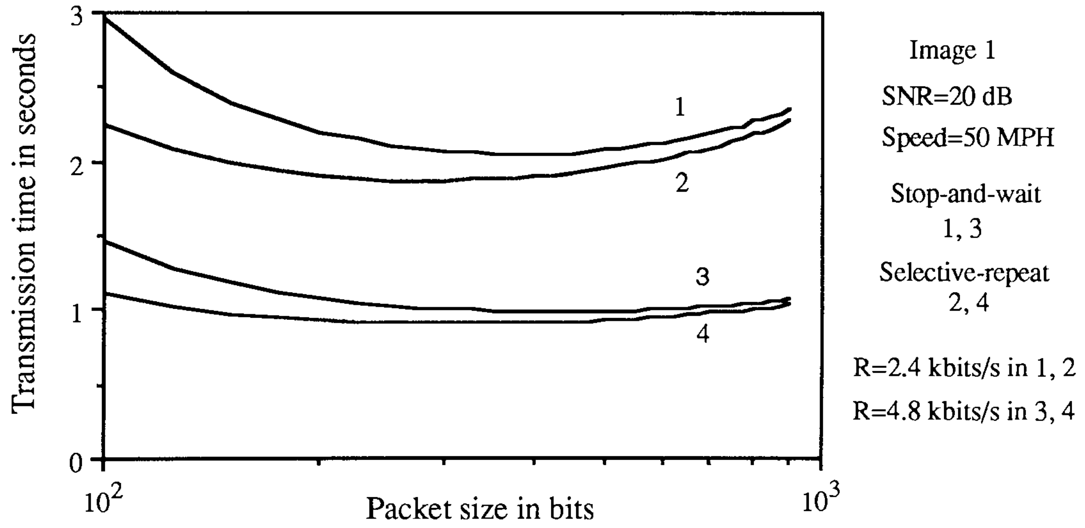


Fig. 7.10 Transmission time for the test image 1 versus packet size using ARQ techniques (error file 2 and 4).

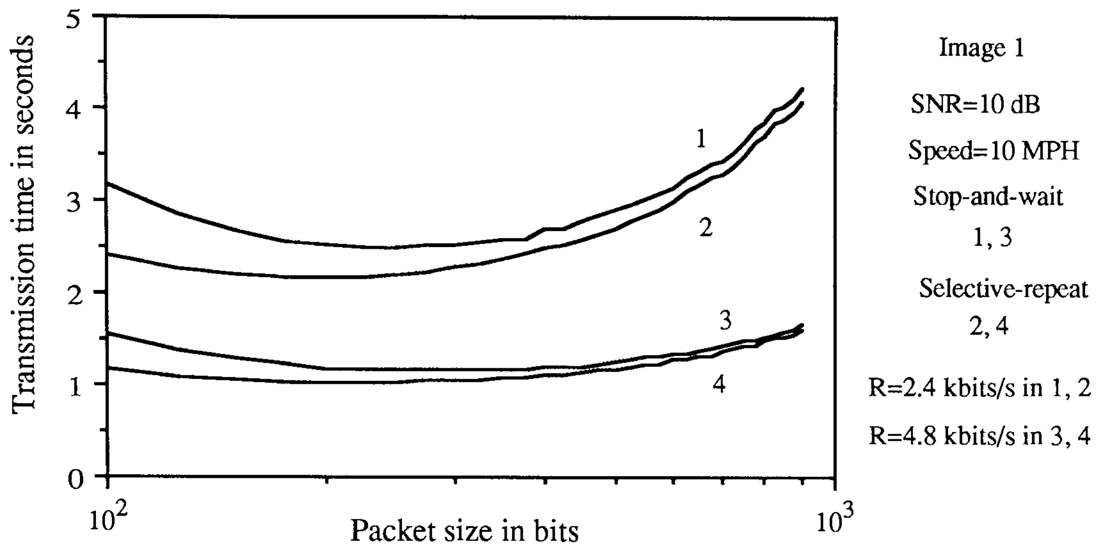


Fig. 7.11 Transmission time for the test image 1 versus packet size using ARQ techniques (error file 5 and 7).

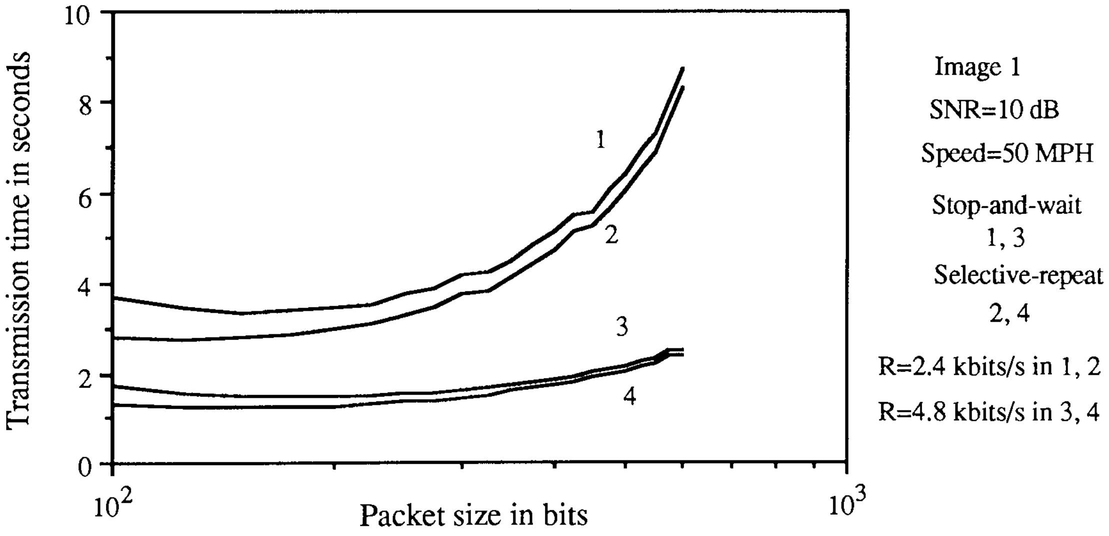


Fig. 7.12 Transmission time for the test image 1 versus packet size using ARQ techniques (error file 6 and 8).

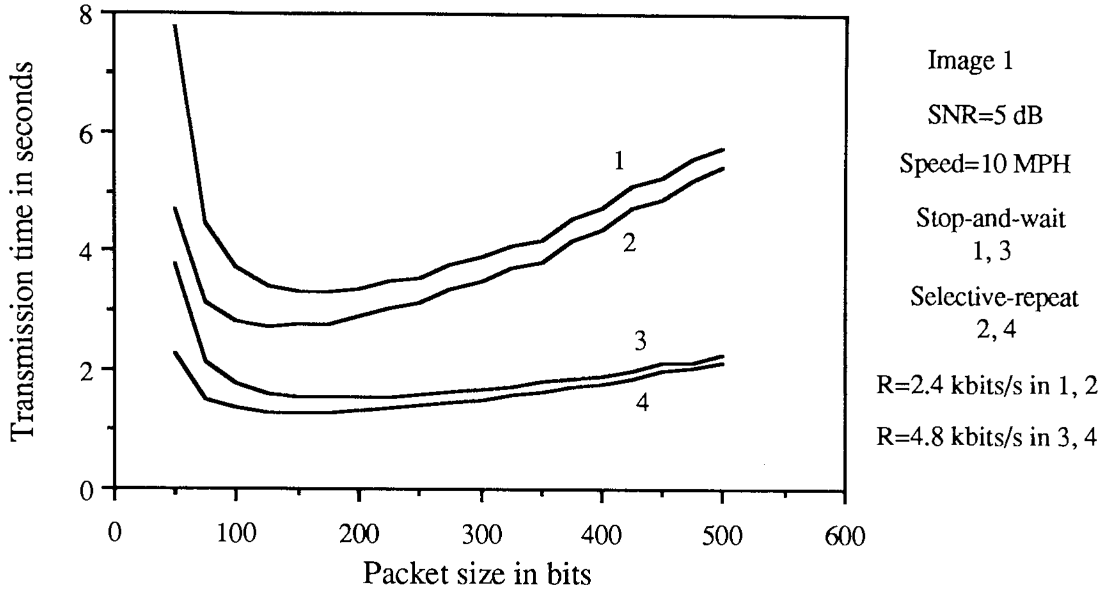


Fig. 7.13 Transmission time for the test image 1 versus packet size using ARQ techniques (error file 9 and 11).

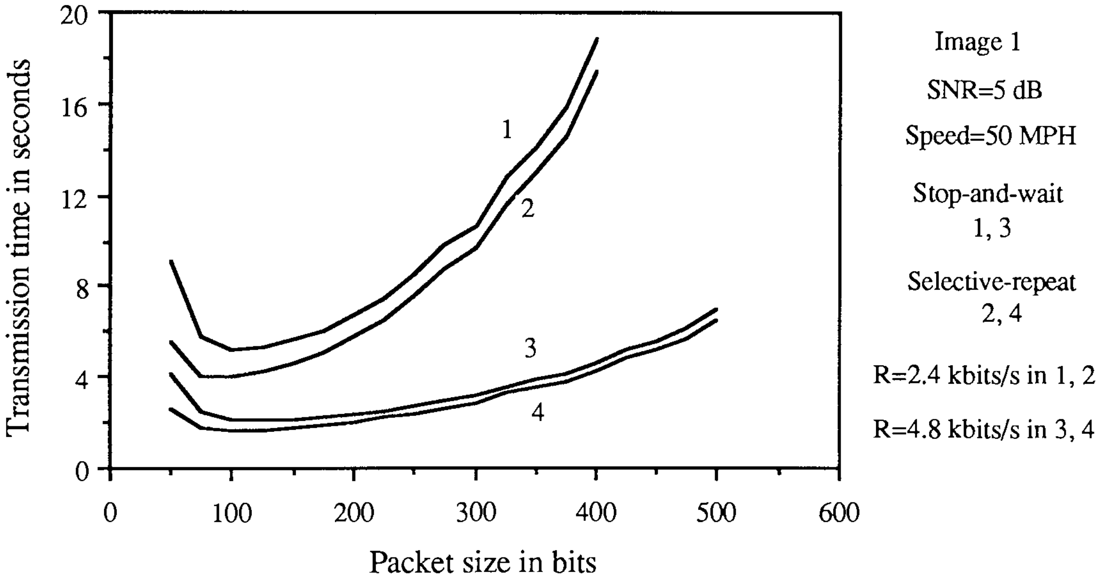


Fig. 7.14 Transmission time for the test image 1 versus packet size using ARQ techniques (error file 10 and 12).

2. Channel Throughput

In chapter 6 expressions for the channel throughput for both stop-and-wait and selective-repeat techniques were presented. Performance results in terms of the channel throughput are now presented. The results are shown as graphs, where each graph shows the channel throughput as a function of the packet size under a certain mobile channel conditions. The conditions of the mobile channels are represented by error files (see chapter 4).

Figures 7.15 and 7.16 show the performance results in terms of the channel throughput as a function of the packet size for the stop-and-wait and selective-repeat ARQ techniques for error files 1 to 4. Figures 7.17 and 7.18 show the results for error files 5 to 8 and Figures 7.19 and 7.20 show the results for error files 9 to 12. It can be seen from these figures that the channel throughput is a function of SNR, vehicle speed and transmission rate. The figures show that optimum values of throughput are obtained at the specific values of packet sizes that also give minimum transmission times [105, 117].

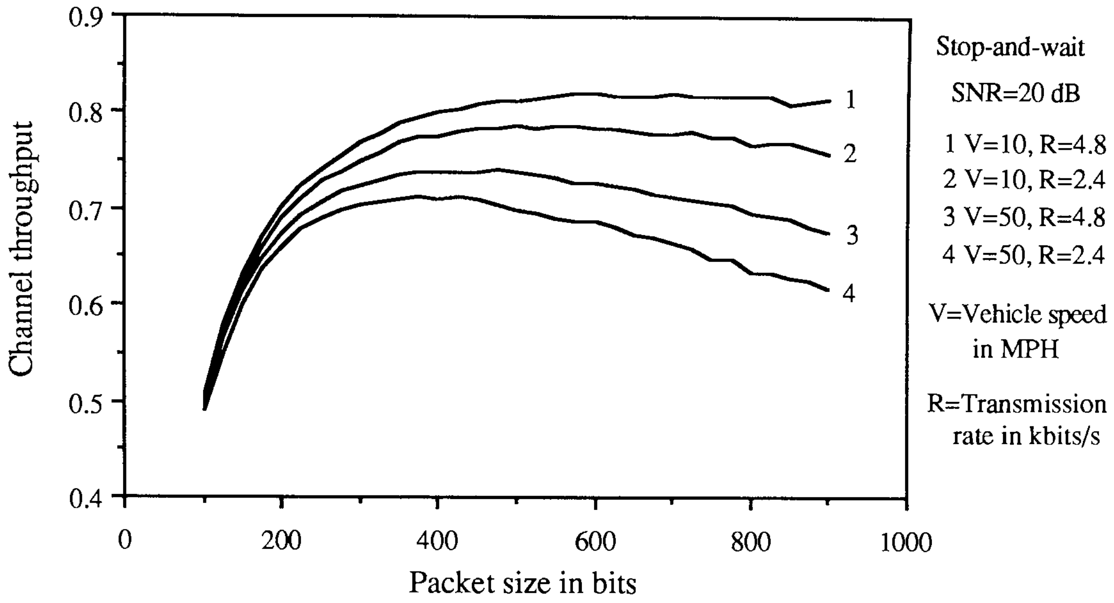


Fig. 7.15 Channel throughput versus packet size using the stop-and-wait ARQ technique for error files 1 to 4.

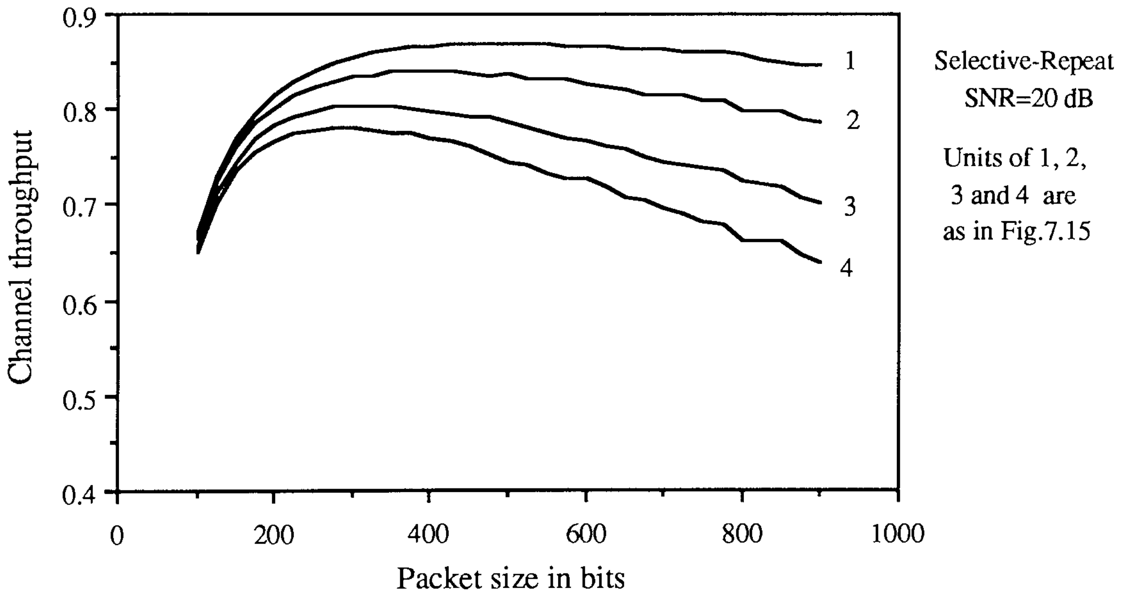


Fig. 7.16 Channel throughput versus packet size using the selective-repeat ARQ technique for error files 1 to 4.

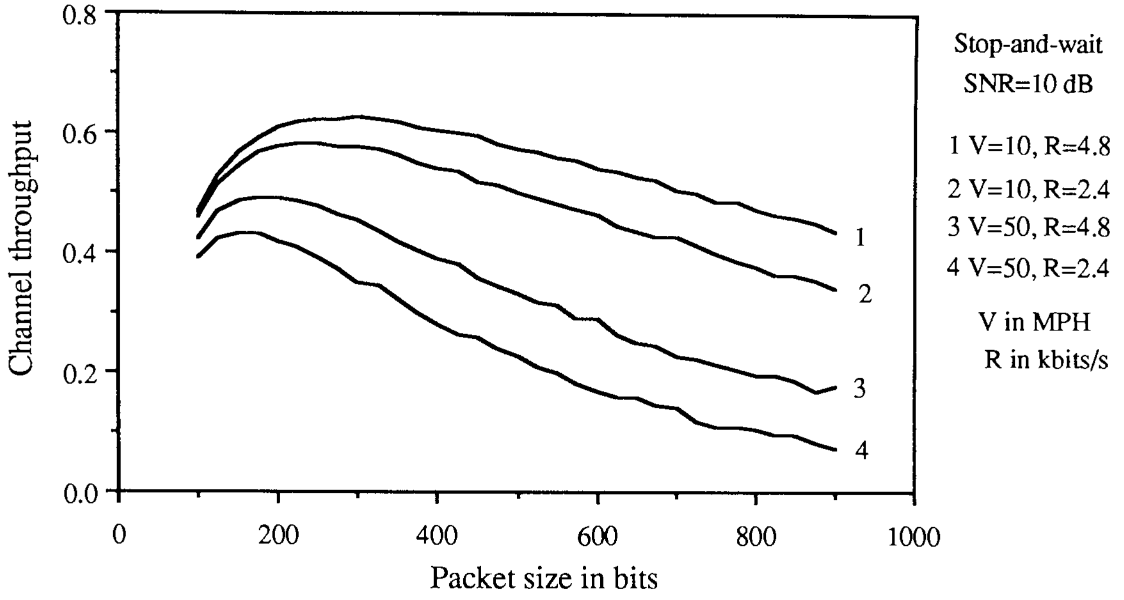


Fig. 7.17 Channel throughput versus packet size using the stop-and-wait ARQ technique for error files 5 to 8.

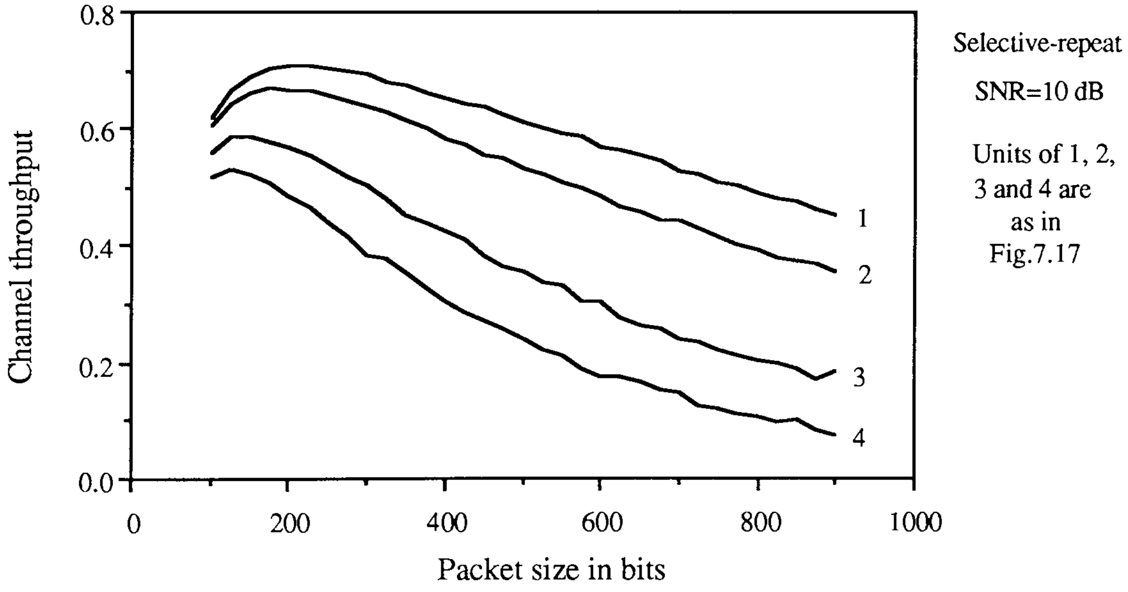


Fig. 7.18 Channel throughput versus packet size using the selective-repeat ARQ technique for error files 5 to 8.

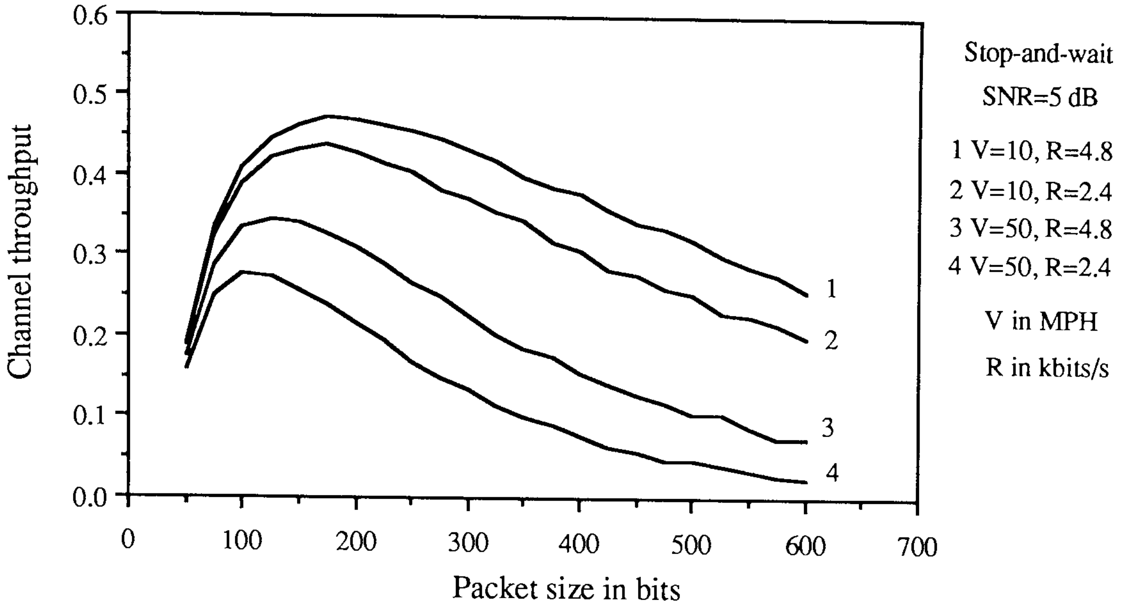


Fig. 7.19 Channel throughput versus packet size using the stop-and-wait ARQ technique for error files 9 to 12.

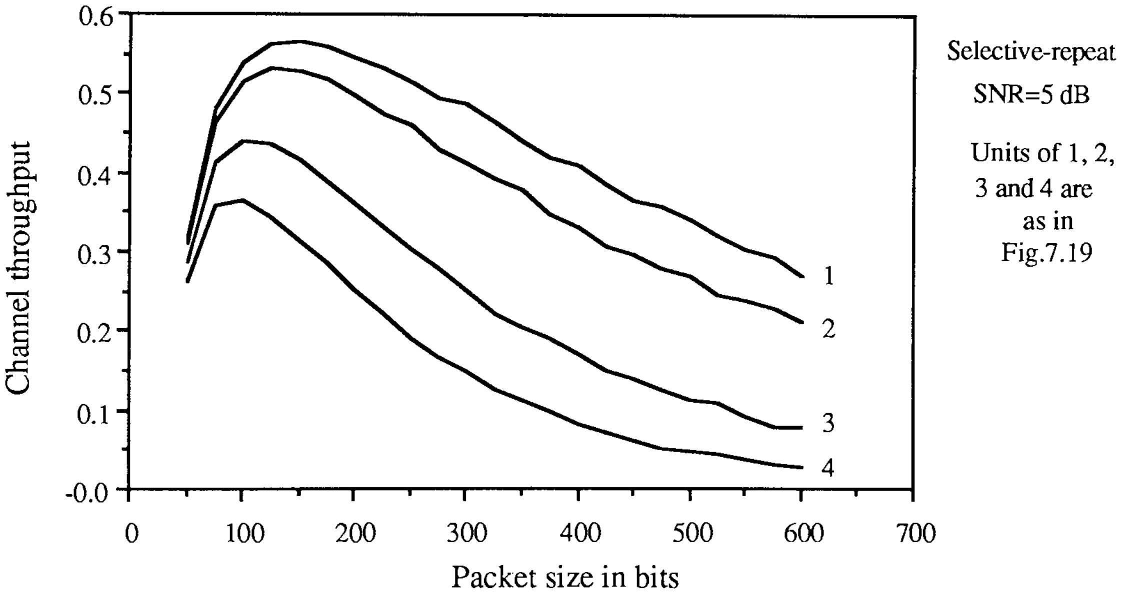


Fig. 7.20 Channel throughput versus packet size using the selective-repeat ARQ technique for error files 9 to 12.

7.5 Summary

In this chapter, the performance results of the transmitted test images 1 and 2 were obtained using FEC codes with interleaving and ARQ methods as channel error protection schemes. Three FEC codes (7, 4, 1), (15, 7, 2) and (73, 45, 4) based on majority-logic decodable codes were evaluated using various interleaving degrees to overcome transmission errors under different mobile channel conditions. The (15, 7, 2) code was selected because it gives good performance under high channel BER. Moreover, the encoding and decoding operations are simple and the size of the matrix storage used for interleaving is reasonable. The subjective performance analysis of the transmitted test images using the (15, 7, 2) with selected values of interleaving shows very good results for mobile channel BERs of 0.0005 and 0.005, in which almost all the received test images were received without errors. For a higher channel BER of 0.017, a significant number of test images were also received without errors. Under such conditions, an average value of 4 or more on the 5-point grade scale was obtained for the subjective assessment tests.

The results of the ARQ schemes show that the packet length of image data to be transmitted has a great effect on the time required to transmit the test images successfully over the mobile channels. It is therefore necessary to choose a packet length that gives minimum transmission time.

CHAPTER 8

CONCLUSIONS

8.1 Conclusions

The research reported in this thesis has been carried out to study methods of transmitting basic line diagram graphic images such as floor plans, street maps ...etc., over digital networks involving mobile terminals at transmission rates of 2400 bits/s and 4800 bits/s. The aim was to receive the graphic images with an acceptable quality and a reasonable transmission time using as simple an approach as possible. It is generally agreed that the communication channel that suffers most from the problem of poor signal quality, multipath fading and high error rates is the mobile channel. For this reason the mobile radio communication channel was considered, since if the images are received with a good quality when transmitted over such channels then they will also be received with a good quality over other channels. The conclusions we obtained from this study can be classified as follows.

1. A general study of image data transmission over communication networks in chapter 2 and 3 has shown that it is unlikely that adequate transmission rates will be available in mobile radio channels that it will make it possible to transmit pictorial information of a television or videoconference quality based on full pixel representation. Low bit-rate stationary images, such as facsimile images and videotex images have been used over low transmission rate channels. It has been shown that geometric encoding used for representing graphics images in computer systems and some videotex systems can be used efficiently to represent the line diagram test images used in this study. Geometric encoding has the advantages that the amount of data required to represent a graphic image is related to the image details. Moreover, the received terminals used to reproduce the images can be of various resolution, according to the requirement of the users. However, because geometric encoding is an efficient source encoding for representing line diagram images, it is to be expected that the encoded image data would be liable to transmission errors.

2. Channel modelling is a very useful technique widely used to represent the characteristics of a channel using computer simulation analysis or a mathematical approach. It has been shown in chapter 4 that the Gilbert-Eillott model using computer simulation can be used to represent accurately digital mobile radio channels. The mobile channel characteristics obtained from the model were very similar to those obtained by field measurements. The model was therefore used as a mobile channel error source to evaluate the performance of the transmitted line diagram test images.

3. The subjective performance results obtained from subjecting the unprotected line diagram test images to transmission errors due to a mobile channel shows that the conditions of the mobile channel seriously affect the quality of the received images (chapter 5). The most significant factors affecting the performance results were the SNR and vehicle speed. An important observation obtained is that for the same channel error rate, the effect on the geometric source encoded image file data of a channel with random errors or short burst errors, due to short fades caused by high vehicle speeds, is much worse than the effect of a channel with long burst errors, due to long fades associated with low vehicle speeds. To obtain acceptable performance results, good mobile channel conditions were required such as a high value of SNR (BER around 0.0005) and a low vehicle speed of 10 MPH. The performance degrades at a high vehicle speed of 50 MPH. For a SNR of 20 dB, an average value of 3.4 or higher on the 5-point grade scale was obtained for the quality and usefulness subjective assessment tests. It has been shown that, at a low vehicle speed, the results of the quality subjective tests give better results than the usefulness subjective tests while, at high vehicle speed, the results of the usefulness subjective tests show better performance. At a lower value of SNR of 10 dB (BER = 0.005), the performance results degrade severely and they were unacceptable to the observers. For the unprotected image data, the performance tests at a lower value of SNR of 5 dB (BER = 0.017) were not carried out because it was expected that the results would degrade more severely in comparison to a SNR of 10 dB. The conclusion was thus reached that channel error protection techniques were

required to ensure that the transmitted encoded source data of the test images can cope with various expected mobile channel conditions.

4. It has been also shown in chapter 5 that image file size, the image shape and the transmission rate also have an effect, although less serious, on the subjective performance of the unprotected test images. An improvement was obtained in the performance of the test image 1, which was visually more predictable and smaller in file size in comparison to the test image 2. For the same channel error rate, a higher transmission rate of 4800 bits/s, which produces longer error bursts, shows a slightly better performance in comparison to the low transmission rate of 2400 bits/s which produces shorter but more frequent error bursts.

5. A general study of error control techniques in digital communication systems, given in chapter 6, revealed that forward error correction (FEC) codes and automatic repeat request (ARQ) schemes have been used widely as channel encoding for reliable data transmission over mobile channels. By considering the nature of mobile channels, where burst errors predominate, it was shown that a combination of an interleaving technique with a random error correcting code is a very useful and simple technique to protect the transmitted image data. In general, the disadvantage of this technique is that interleaved codes cannot be used when the message length is small. However, the size of the test images were long enough for long interleaved codes to be implemented. For the FEC codes, majority-logic decodable codes were used where the decoding procedure is easily implemented.

6. The results obtained from the simulation of the forward error correcting codes (chapter 7) show that the (15, 7, 2) code with interleaving can be used effectively to overcome transmission errors over a range of channel BER up to 0.017. The results of the subjective tests obtained from subjecting the encoded image file data with interleaving to a channel BER of 0.0005 (SNR = 20 dB) show that all test images were received

without errors. For a channel BER of 0.005 (SNR = 10 dB) a large number of test images were received without errors (Table 7.2). At a higher channel BER of 0.017 (SNR = 5 dB) a significant number of test images were also received without errors (Tables 7.3 to 7.6). At such high channel BER, an average value of about 4 or more on the 5-point grade scale was obtained for the quality and usefulness subjective assessment tests. The transmission times required for the protected test images 1 and 2 using a transmission rate of 2400 bits/s and under different other mobile channel conditions were 3.13 and 6.7 seconds respectively. The conclusion is thus reached that an FEC code with interleaving can be used effectively to protect the transmitted test images under different mobile conditions.

7. The results obtained using ARQ schemes for protecting the transmitted image file data show that the packet size has a great effect on the time required to transmit the test images without errors over a mobile channel. For different mobile channel conditions, different optimum packet sizes were obtained. It was shown that the best performance results (larger packet size and smaller transmission time) were obtained at high values of SNR, low vehicle speed and high transmission rate. At a SNR of 20 dB and using the stop-and-wait ARQ scheme, minimum transmission times of 2.05 and 4.4 seconds were required for the test images 1 and 2. At a SNR of 20 dB, the stop-and-wait ARQ scheme shows better performance in terms of transmission times in comparison to the FEC code described above in 6. At a SNR of 10 dB, minimum transmission times of 3.38 and 7.33 were required for the test images 1 and 2. Compared to the case of the FEC code, it can be seen that almost similar results were obtained in terms of transmission times. At a lower value of SNR of 5 dB, the performance of the ARQ degrades in comparison to the FEC code. Under such conditions, the optimum packet size was about 100 bits and the transmission times required for the test images 1 and 2 were about 5.25 and 11.38 seconds. The performance results for the ARQ techniques show that the selective-repeat ARQ scheme always gives an improvement factor greater than the stop-and-wait scheme. However, it's implementation is more difficult in practice.

The conclusion is thus reached that for low values of channel BER of 0.0005 the ARQ scheme can be used more efficiently in terms of transmission times than FEC to protect the test images. For high channel BER of 0.017, the FEC with interleaving shows better performance.

8.2 Suggestions for Further Work

The work in this thesis provides the essential requirements to transmit line diagram graphic images such as street maps and floor plans over digital networks involving mobile terminals. To this extent the work is complete in it s present form. It has been shown that transmission of image data over mobile terminals has already seen great demands and it is expected that the demand will increase in future. Therefore, further work could be carried out as follows:

Examination of the behaviour of geometric image coding where the mobile channel error rate starts to exceed 0.017. This would require consideration of error protection codes with a higher error correcting capability, e.g., concatenated codes or combined (hybrid) FEC / ARQ codes.

Further work could also be carried out to observe the possibility of using higher transmission rates for image data transmission over mobile channels. At higher transmission rates, the use of test images with greater detail, such as large diagrams of electricity or gas network boards, could be also studied.

Finally, to prove the operation of the proposed system in practice, it is necessary to implement the system in hardware for field trial assessment.

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