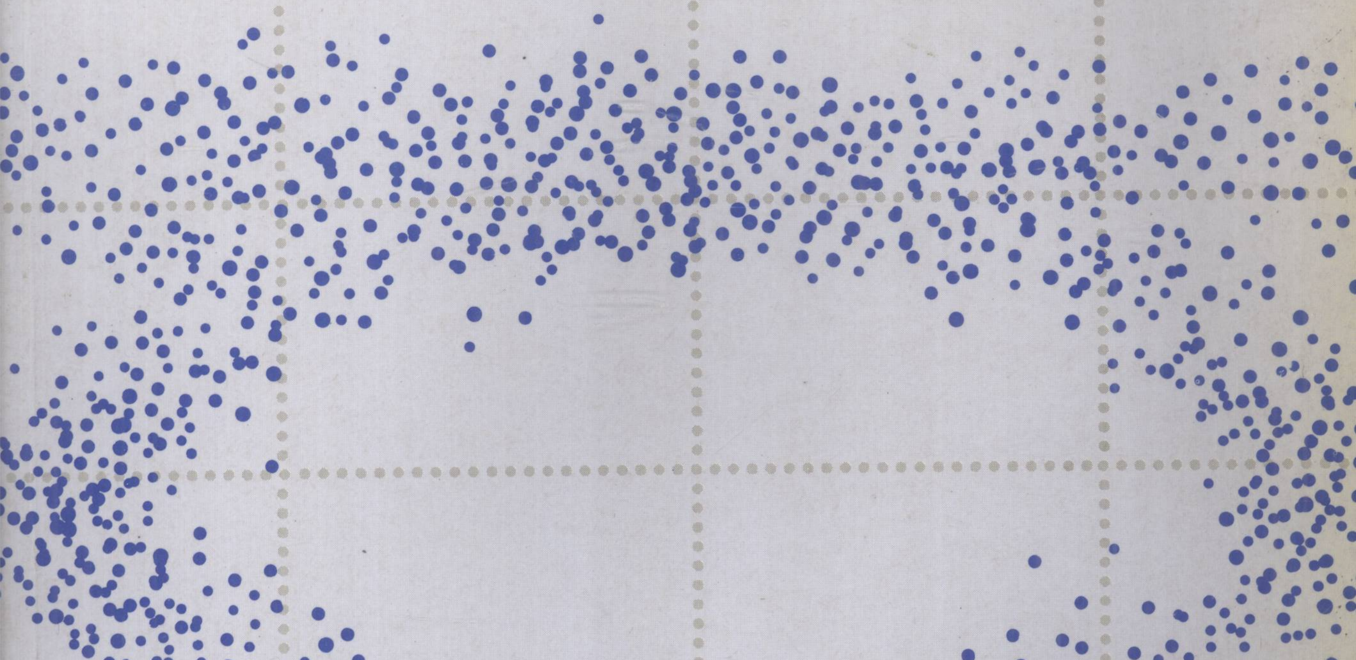
Digital Signal Transmission



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CAMBRIDGE
UNIVERSITY PRESS

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, Victoria 3166, Australia

First published 1992

Printed in Great Britain at the University Press, Cambridge

A catalogue record of this book is available from the British Library

Library of Congress cataloguing in publication data
Bissell, C. C. (Chris C.)
Digital signal transmission / C.C. Bissell, D.A. Chapman.
p. cm.
Includes bibliographical references and index.
ISBN 0–521–41537–3. – ISBN 0–521–42557–3 (pbk.)
1. Digital communications. 2. Signal processing – Digital techniques. 3. Integrated services digital networks. I. Chapman, D.A. (David A.) II. Title.
TK5103.7.B54 1992
621.382 – dc20 91/40848 CIP

ISBN 0 521 41537 3 hardback
ISBN 0 521 42557 3 paperback

VN

This textbook will provide both undergraduates and practising engineers with an up-to-date and thorough grounding in the concepts of modern digital transmission. The book is not encyclopaedic; rather, it selects the key concepts and processes and explains them in a deliberately pedagogic style. These concepts and processes are then illustrated by a number of system descriptions.

The book is divided into three parts. The longest, Part 2, describes the basic processes of digital transmission, such as matched filter detection, pulse shaping, line coding, channel coding, error detection and correction, etc. Understanding the concepts behind these processes requires a grasp of basic mathematical models, and this is provided in Part 1. Finally, to put the processes in context, Part 3 describes elements of the public switched telephone network. The text is written throughout in a modern, digital context, and is comprehensively illustrated with helpful figures. Although the mathematical models (time- and frequency-domain concepts) have wider relevance, they are developed specifically for modelling digital signals. The processes described are those found in current transmission systems, and the description of the PSTN includes an outline of newly formulated standards for the synchronous digital hierarchy (SDH), SONET and for broadband ISDN (ATM).

The book will be of great value to 2nd and 3rd year undergraduates studying telecommunications, as well as to graduate trainees and practising engineers. It is appropriate for either private study or as a text associated with a taught telecommunications course. The many worked examples and exercises with solutions will be particularly helpful.

Digital signal transmission

Preface

In this book we try to give a representative (but not comprehensive) treatment of the digital transmission of signals. Our main aim has been to render the material truly accessible to second or third year undergraduate students, practising engineers requiring updating, or graduate physicists or mathematicians beginning work in the digital transmission sector of the telecommunications industry. This has led to a book whose important features are:

- A limited number of topics, dealt with in depth
- An emphasis on the engineering context and interpretation of mathematical models
- Relevance to both students and practising engineers

Engineering is a pragmatic activity, and its models and theory primarily a means to an end. As with other engineering disciplines, much of telecommunications is driven by practicalities: the design of line codes (Chapter 6), or the synchronous digital hierarchy (Chapter 8), for example, owe little to any complicated theoretical analysis of digital telecommunications! Yet even such pragmatic activities take place against a background of constraints which telecommunications engineers sooner or later translate into highly abstract models involving bandwidth, spectra, noise density, probability distributions, error rates, and so on. To present these vitally important ideas – in a limited number of contexts, but in sufficient detail to be properly understood by the reader – is the main aim of this book. Thus time- and frequency-domain modelling tools form one constant theme (whether as part of the theory of pulse shaping and signal detection in Chapter 4, or as a background to the niceties of optical receiver design in Chapter 9); the constant battle against noise and the drive to minimise errors is another.

Chapter 1, and the brief introductions to the three main parts, describe the scope of the book more fully. We believe there are already enough encyclopaedic reference texts and books of applied mathematics masquerading as introductions to telecommunications! We have tried to write a book in which the theory illuminates, rather than obscures, the engineering; and a book which will enable the reader subsequently to approach more advanced reference material (specialist texts and manufacturers' literature, for example) without being overwhelmed.

Acknowledgments

Large parts of this text are derived from our contributions to the Open University course T322 Digital Telecommunications (Open University Press, 1990), although the material has been considerably modified, updated, and extended. Our general approach has been greatly influenced by discussions within the T322 course team, and in particular by the stimulating ideas of the Course Chair, Gaby Smol. Around 60% of the figures used here are reproduced directly from T322 by kind permission of the Open University. Thanks are also due to Mr P.J. King of GPT and Dr V.S. Shukla of GTE for advice on the contents of Chapter 8. Any errors, however, remain our own responsibility.

Some of the text was written while one of us (Bissell) was on study leave at Twente University in the Netherlands; the hospitality and accommodation provided by the Vakgroep Tele-Informatica is gratefully acknowledged.

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1

Introduction

The topic of digital signal transmission is an enormous one, and cannot be covered completely in a book this size. The aim of this introduction is to set the material of later chapters into the general context of modern telecommunication systems, and to outline what will be covered in detail later and what will not. Some suggestions will also be made about how to use the book.

1.1 The Integrated Services Digital Network

In most countries, telecommunications services are evolving rapidly from a collection of separate, and largely incompatible, systems (telephone, telex, public and private data networks, and so on) towards a universal network, in which a wide variety of services are integrated using a common (digital) form of transmission.

Fig. 1.1 shows, in much simplified form, how two offices (or factories, or homes) might be interconnected through such an *Integrated Services Digital Network* (*ISDN*). At each office, digital signals from a number of different audio, video or data terminals are connected, via appropriate network terminating equipment (NTE), to an exchange termination (ET) within the ISDN. Whatever their origin, the signals are transmitted to their destinations over digital links which may include optical fibres, metallic cables, terrestrial or satellite microwave channels, and so on. To the network it is completely immaterial whether the signal carries a telephone conversation, computer data, or the reading on an electricity meter.

Chapter 8 will look in detail at some aspects of the evolution of existing telephone networks towards an ISDN.

A universal network should eventually prove more flexible and cheaper than a number of separate networks, each providing only a narrow range of services. Ultimately such a network may even subsume broadcast radio and television! However, existing telecommunications networks represent enormous investment, and cannot be simply abandoned and replaced by an ISDN. Evolution towards a universal network is therefore gradual, and depends upon the adaptation of existing systems.

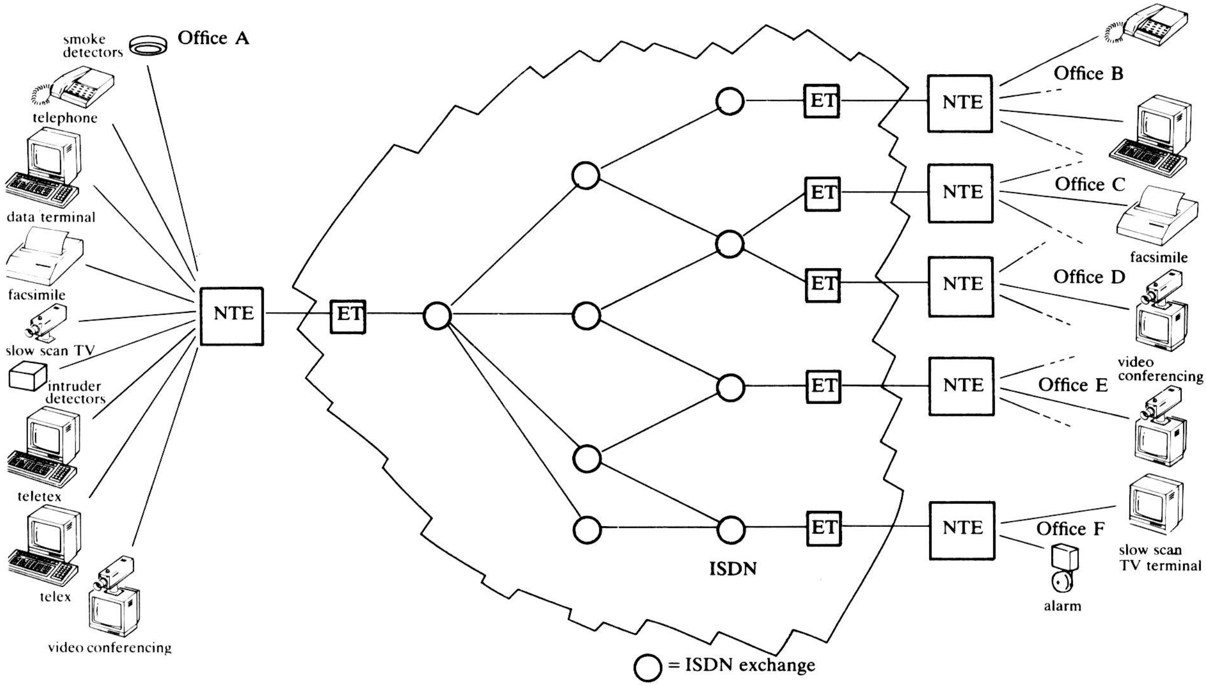

Fig. 1.1. Two offices linked by an integrated services digital network (ISDN).

1.2 Standards

A moment's reflection on the nature of an ISDN should bring home the importance of standards for the success of such a multi-purpose, wide-ranging system. Standards are required at all levels – from internationally agreed regulations on the interconnection of national ISDNs, to the details of voltages and wiring for the connection of individual terminals to NTEs.

Standards have long been vital for the telecommunications industry, and many sets of national and international regulations have been published. Two of the most important bodies are the *CCITT* (French initials for International Telegraph and Telephone Consultative Committee – part of the International Telecommunications Union (ITU), affiliated to the United Nations Organization) – and the *ISO* (International Organization for Standardization). CCITT recommendations are issued approximately every four years, as a set of volumes universally referred to within the telecommunications industry by their colour: the current set, published in 1989, are the *Blue Books*. Many references to CCITT recommendations will be made in subsequent chapters.

1.3 Convergence of telecommunications and computing

Implicit in Fig. 1.1 is a comparatively recent phenomenon known as the 'convergence' of digital telecommunications and computing. As the use of computers in business, industry and even the home to store and process information has grown, so there has been an increasing demand for the electronic transmission of such information – both within a single organisation via local networks, and from one organisation to another over public and private networks.

At the same time, most recent advances in telecommunications have involved digital techniques for both the transmission and processing of signals. As far as transmission is concerned, the reasons include:

– the fact that the build-up of noise on a conveyed message can be virtually eliminated by the process known as regeneration (outlined below), and the error rate can thus be kept very low

Part II of this book is concerned mainly with such properties of digital signals, and with techniques for processing, transmission and error detection/correction.

– the possibility of detecting and even correcting those errors which do occur during signal processing and transmission (discussed in Chapters 5 and 6)

– the development of high capacity transmission media, such as optical fibres, which are particularly suited for digital transmission

Furthermore, recently developed digital electronic devices are cheaper, more reliable and consume less power than the analogue circuits previously used for signal processing.

1.4 Open Systems Interconnection

The convergence between telecommunications and computing has led to a need for standards which deal with much more than simply the conveying of a digital signal from transmitter to receiver at a suitably low error rate. Systems which offer, say, facilities for processing data on one computer using programs accessed remotely on another, or which allow complex graphics to be transmitted from one make of personal computer to another in a different country, clearly require a degree of standardisation quite unlike that traditionally associated with the telecommunications industry! An important strategy has emerged over the last decade or so to deal with such complexity, based round the ISO Open Systems Interconnection (OSI) Basic Reference Model. Whole books have been devoted to the OSI reference model, so the description which follows is

See, for example, MacKinnon, McCrum & Sheppard.

necessarily an over-simplification. It is included for two reasons: first, because it has become standard practice for descriptions of modern digital telecommunication systems to refer to the OSI model, so the subject matter of this book needs to be placed in this general context; second, because one of the central features of the model – the concept of *layers* – is used as a framework for Part 2 of this book.

The origins of the OSI reference model in computer communications is evident in some of the terminology used. Thus the term *application* is used to refer to the complete set of processes involved in a particular customer service (rather as in 'applications program'): electronic mail or airline ticket reservation are examples of applications in this sense. A system is called *open* if it is capable of communicating directly with other open systems of an appropriate type. An open system conforming to OSI standards carries out all communication processes for the applications it serves in a standard, agreed way, so it can work with other open systems running cognate applications. For example, a particular airline might run Application A to handle its own flight bookings, while a travel agency runs Application B dealing with bookings with a number of different airlines. OSI is not concerned with the booking process itself (this is a function of the applications), but rather with the communication systems. The latter consist mainly of software processes which allow the airline and travel agency applications to interact.

Perhaps the most distinctive feature of the OSI reference model is its layered architecture, in which a hierarchy of abstraction is identified in the overall communication process. This is shown in Fig. 1.2. The precise functions of each individual layer are not a major concern of this book, but can be briefly summarised as follows:

physical layer – does whatever is needed to convey bit streams between the layer immediately above it and the physical transmission medium. This may include the use of a modem or other signal processing to produce a physical signal appropriate to the medium.

data link layer – ensures the correct, effectively error-free transmission of data between individual nodes in the network.

network layer – deals with the routing and switching of the data over the complete network, including the orderly re-establishment of connection in the case of disruption.

transport layer – sets up end-to-end connections, possibly selecting from more than one network if available.

session layer – organises the whole set of transport connections

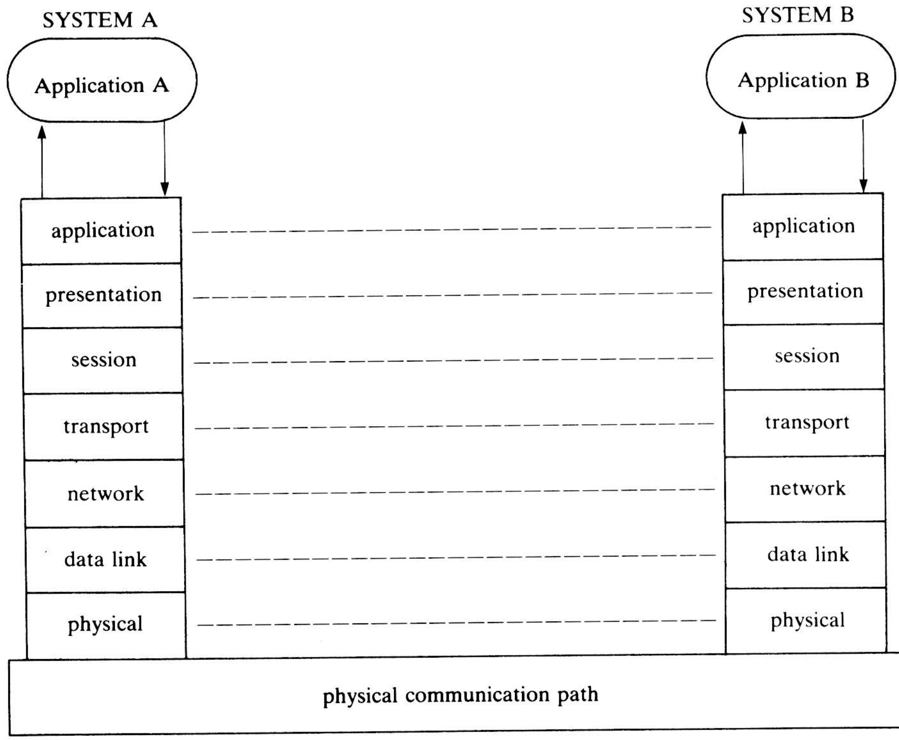

Fig. 1.2. Two applications linked directly by OSI systems. Horizontal 'virtual links' can be set up between any pair of 'peer' layers.

required for a given session; carries out various other functions relating to data interchange.

presentation layer – deals with the rules for representing information, agrees a common syntax such as the use of ASCII code.

application layer – deals with the semantics of the communication, normally specific to the particular application. In the ticket reservation example, a common language for referring to flight numbers, times, and so on, would be required.

In the OSI model, communication takes place vertically as requests for action are passed from one layer to another. Suppose, for example, that the system A transport layer of Fig. 1.2 requests from the network layer a connection to system B. The network layer passes on an appropriate request to the data link layer, and the data link layer to the physical layer. A suitable message is then transmitted over the physical communication path, and ultimately the request for a connection reaches the network layer of system B. To the two network layers, however, it is as though there is a direct horizontal communication channel – known as a *virtual channel* – between them. This is an important feature of the OSI model,

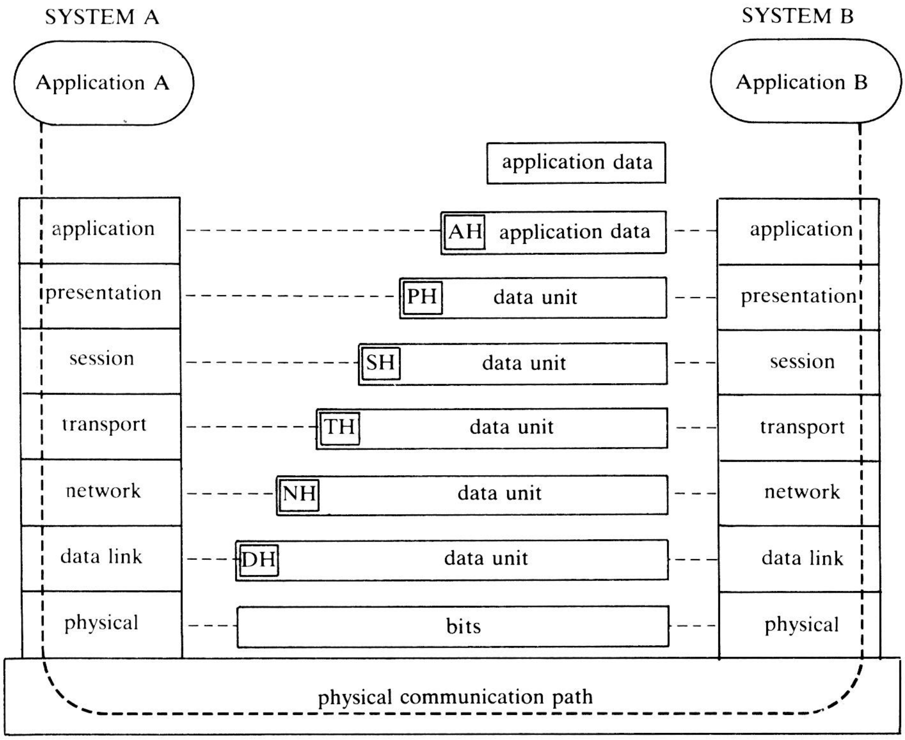

Fig. 1.3. Vertical flow of data and protocol information.

and is represented by the dashed lines in Fig. 1.2. Horizontal communication over virtual channels is specified in terms of so-called *peer protocols*. The protocol information required by the individual layers is transmitted as a set of *headers* added to the application data on its way down one stack and stripped off on its way up the other, as shown in Fig. 1.3. The price to be paid for the flexibility of OSI standardisation is thus the transmission of a large data overhead.

In OSI terminology, this book is almost entirely concerned with the physical layer – that is, with techniques used to transmit digital signals reliably over particular communication paths. Some aspects of Parts 2 and 3, however, are related to higher-layer OSI functions. The general notion of a layer model, in which each layer adds an overhead as the price of some desirable feature, will also reappear in Part 2.

1.5 Analogue and digital signals

The term 'digital signal' has been used so far without definition, on the assumption that the reader will have some familiarity with digital systems.

Now, however, it is time to be more precise, and to turn to digital signal transmission in detail. For the purposes of this book, a digital signal is one which consists of a sequence of symbols taken from a finite set. The text of this book can therefore be thought of as a digital signal: it is made up of a finite number of distinct symbols – the Roman alphabet (and part of the Greek), in various founts and formats, together with punctuation marks (including spaces), the digits 0 to 9, and mathematical symbols.

The simplest digital signal – a *binary signal* – uses only two symbols or states, almost always denoted 0 and 1. For transmission over a physical communication path, these binary digits or *bits* must be represented in some appropriate way. A number of typical binary signals are shown in Fig. 1.4. In parts (a) and (b) the binary states are represented by two different voltage levels in a way known as *positive logic* if the voltage used to represent binary 1 is higher than that used for binary 0, and *negative logic* if the converse is true. The pulses shown are *non-return to zero* (*NRZ*): each voltage level is held at the appropriate value for the whole

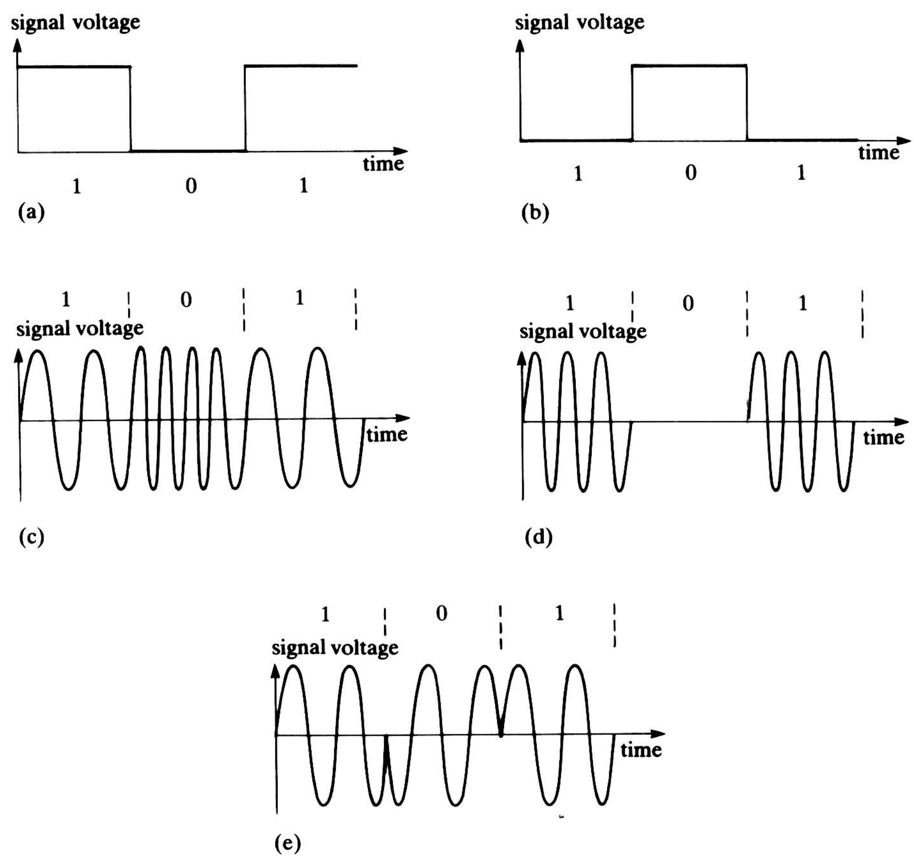

Fig. 1.4. Some common types of binary digital signals.

symbol period. (A common alternative is for the non-zero voltages to last for only part (usually half) of the symbol period: this is *return-to-zero* (*RZ*) signalling.) The waveforms of parts (a) and (b) are both *unipolar* – voltages of one polarity only are used, in contrast to *bipolar* (or simply *polar*) signalling, where both positive and negative voltages are used in a single digital waveform. In part (c) of the figure, two different frequencies are used to represent the binary states, while in (d) a single frequency is turned on and off. Finally in (e) the phase of a transmitted sinusoid carries the information.

The terminology used to describe digital waveforms is not standard, and readers should be on their guard against confusion. For example, in North America the term bipolar has a different meaning, as will be described in Chapter 5.

One of the most important features of digital signals is the way in which the effects of noise and interference can be virtually eliminated. Fig. 1.5 illustrates the general principle. Part (a) shows a binary signal representing the bit stream 10110001. After transmission over a noisy, distorting channel, the received signal might be as shown in part (b). Although the signal has a very different appearance from that transmitted, it is possible to obtain a perfect replica of the original by means of a circuit which

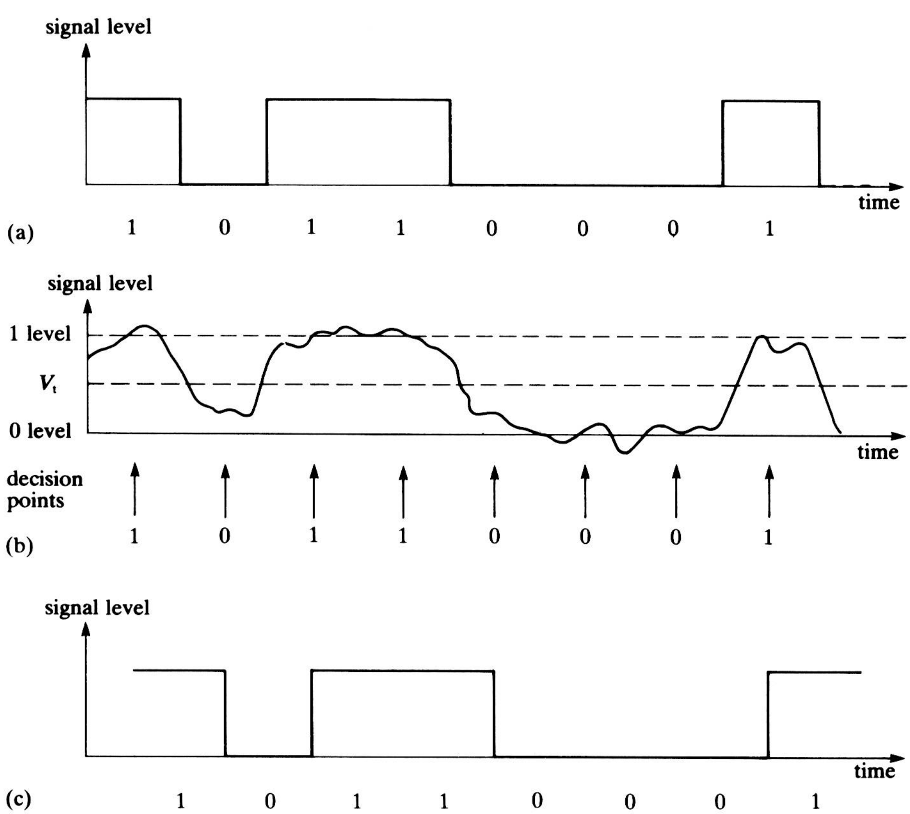

Fig. 1.5. Binary waveforms: (a) transmitted, (b) received and distorted, (c) after regeneration.