

DIGITAL AND ANALOG COMMUNICATION SYSTEMS

Eighth Edition

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PEARSON

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*To my wife, Margaret Wheland Couch,
and to our children,
Leon III, Jonathan, and Rebecca*

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Library of Congress Cataloging-in-Publication Data

Couch, Leon W.

Digital & analog communication systems / Leon W. Couch, II.—8th ed.
p. cm.

ISBN-13: 978-0-13-291538-0 (alk. paper)

ISBN-10: 0-13-291538-3 (alk. paper)

1. Telecommunication systems. 2. Digital communications. I. Title.

II. Title: Digital and analog communication systems.

TK5101.C69 2013

384—dc23

2011038659

PEARSON

ISBN-10: 0-13-291538-3

ISBN-13: 978-0-13-291538-0

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PREFACE

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Block Codes

Convolutional

Code Division

Code Division

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and the average information would have been less than 12 bits. For example, if half of the 12-bit words (2,048 of the possible 4,096) have probability of occurrence of $P_j = 10^{-5}$ for each of these words (with a corresponding $I_j = 16.61$ bits) and the other half have $P_j = 4.78 \times 10^{-4}$ (for a corresponding $I_j = 11.03$ bits), then the average information is $H = 11.14$ bits.

The rate of information is also important.

DEFINITION. The *source rate* is given by

$$R = \frac{H}{T} \text{ bits/s} \quad (1-9)$$

where H is evaluated by using Eq. (1-8) and T is the time required to send a message.

The definitions previously given apply to digital sources. Results for analog sources can be approximated by digital sources with as much accuracy as we desire.

1-10 CHANNEL CAPACITY AND IDEAL COMMUNICATION SYSTEMS

Many criteria can be used to measure the effectiveness of a communication system to see if it is ideal or perfect. For digital systems, the optimum system might be defined as the system that minimizes the probability of bit error at the system output subject to constraints on transmitted energy and channel bandwidth. Thus, bit error and signal bandwidth are of prime importance and are covered in subsequent chapters. This raises the following question: Is it possible to invent a system with no bit error at the output even when we have noise introduced into the channel? This question was answered by Claude Shannon in 1948–1949 [Wyner and Shamai, 1998; Shannon, 1948, 1949]. The answer is yes, under certain assumptions. Shannon showed that (for the case of signal plus white Gaussian noise) a channel capacity C (bits/s) could be calculated such that if the rate of information R (bits/s) was less than C , the probability of error would approach zero. The equation for C is

$$C = B \log_2 \left(1 + \frac{S}{N} \right) \quad (1-10)$$

where B is the channel bandwidth in hertz (Hz) and S/N is the signal-to-noise power ratio (watts/watts, not dB) at the input to the digital receiver. Shannon does not tell us how to build this system, but he proves that it is theoretically possible to have such a system. Thus, Shannon gives us a theoretical performance bound that we can strive to achieve with practical communication systems. Systems that approach this bound usually incorporate error-correction coding.

Example 1-4 CHANNEL CAPACITY

For a case of a telephone line with a bandwidth of 3,300 Hz, plot the channel capacity of the telephone line as a function of the S/N over a range of 0–60 dB. For the solution, see and run the MATLAB file Example1_4.m.

In analog systems, the optimum system might be defined as the one that achieves the largest signal-to-noise ratio at the receiver output, subject to design constraints such as channel bandwidth and transmitted power. Here, the evaluation of the output signal-to-noise ratio is of prime importance. We might ask the question, Is it possible to design a system with infinite signal-to-noise ratio at the output when noise is introduced by the channel? The answer is no. The performance of practical analog systems with respect to that of Shannon's ideal system is illustrated in Chapter 7. (See Fig. 7-27.)

Other fundamental limits for digital signaling were discovered by Nyquist in 1924 and Hartley in 1928. Nyquist showed that if a pulse represents one bit of data, noninterfering pulses could be sent over a channel no faster than $2B$ pulses/s, where B is the channel bandwidth in hertz. This is now known as the dimensionality theorem and is discussed in Chapter 2. Hartley generalized Nyquist's result for the case of multilevel pulse signaling, as discussed in Chapters 3 and 5.

The following section describes the improvement that can be obtained in digital systems when coding is used and how these coded systems compare with Shannon's ideal system.

Digital
source

1-11 CODING

If the data at the output of a digital communication system have errors that are too frequent for the desired use, the errors can often be reduced by the use of either of two main techniques:

- Automatic repeat request (ARQ)
- Forward error correction (FEC)

In an ARQ system, when a receiver circuit detects parity errors in a block of data, it requests that the data block be retransmitted. In an FEC system, the transmitted data are encoded so that the receiver can correct, as well as detect, errors. These procedures are also classified as *channel coding* because they are used to correct errors caused by channel noise. This is different from *source coding*, described in Chapter 3, where the purpose of the coding is to extract the essential information from the source and encode it into digital form so that it can be efficiently stored or transmitted using digital techniques.

The choice between using the ARQ or the FEC technique depends on the particular application. ARQ is often used in computer communication systems because it is relatively inexpensive to implement and there is usually a duplex (two-way) channel so that the receiving end can transmit back an acknowledgment (ACK) for correctly received data or a request for retransmission (NAC) when the data are received in error. FEC techniques are used to correct errors on simplex (one-way) channels, where returning of an ACK/NAC indicator (required for the ARQ technique) is not feasible. FEC is preferred on systems with large transmission delays, because if the ARQ technique were used, the effective data rate would be small; the transmitter would have long idle periods while waiting for the ACK/NAC indicator, which is retarded by the long transmission delay. We concentrate on FEC techniques in the remainder of this section.

Communication systems with FEC are illustrated in Fig. 1-4, where encoding and decoding blocks have been designated. Coding involves adding extra (redundant) bits to the data stream so that the decoder can reduce or correct errors at the output of the receiver.

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