COMMUNICATION AND RADAR SYSTEMS

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PRENTICE-HALL, INC., *Englewood Cliffs, N.J. 07632*

Library of Congress Cataloging in Publication Data

TZANNES, N. S. (NICOLAOS S.) (date)
Communication and radar systems.

Bibliography: p.
Includes index.
1. Radar. 2. Telecommunication. I. Title.
TK6575.T95 1985 621.3848 84-2005
ISBN 0-13-153545-5

Editorial/production supervision
and interior design: *Theresa A. Soler*
Manufacturing buyer: *Anthony Caruso*

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-153545-5 01

Prentice-Hall International, Inc., *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall of Southeast Asia Pte. Ltd., *Singapore*
Whitehall Books Limited, *Wellington, New Zealand*

PREFACE

Most graduating engineers know nothing about radar; it is not part of their undergraduate or, in most cases, graduate programs. This was acceptable when radar was used only by the military, but now radar has crept into many civilian applications, and the time is ripe for a change.

I first toyed with the idea of teaching a course on radar systems to last-year electrical engineering students during the early 1980s. My first problem was a text. Although there was a plethora of books on radars, all of them were written for the specialist or the advanced graduate student. My immediate reaction was to develop my own notes, leading possibly to a new book suitable for the endeavor at hand. Soon, however, I realized that such an effort would be fruitless. The undergraduate electrical engineering curriculum was already packed with courses and there was little if any room for radar systems, even as an elective. There was only one alternative under these conditions, and that was to combine the material with an already existing course.

The present book has been written with the belief that radar systems are a natural part of communication systems. The two fields have enough in common that the final result of their combination *is* much less than the sum of the two fields. Even so, a new book had to be written on the combined subjects, as the many excellent existing texts on communications have very little or nothing on the subject of radar systems. It is my hope that the way I have combined the two fields makes their joint study comprehensible and easy to grasp.

The first part of the book (chapters 1-10) covers the analysis of communication and radar systems in a noise-free regime; an approach taken for pedagogical reasons. Chapter 1 is an introductory general discussion on communication and radar systems, an effort to point out their similarities and differences, and to lay the foundation for their joint analysis. Chapter 2 gives background material on signal analysis of the type usually found in communication and radar systems books; it is presented here in a manner useful for both. The remainder of the chapters cover communication and radar systems in a parallel fashion (AM communication systems followed by AM radar systems and so on) a method that results in saving time and space, and that enables the reader to consolidate knowledge by comparison. It should be noted that the joint analysis of radar systems had to be presented in a way that violates the usual order of presentation in radar books. In any event, I now feel that this order of presentation serves educational purposes much better than the traditional one.

The second part of the book (chapters 11–15) covers the analysis of both types of systems in the presence of additive noise. Chapters 11 and 12 comprise the usual background material on probability and random processes, which is the foundation for the mathematical treatment of noise. Chapter 13 looks at some typical communication systems with an eye on performance in the presence of noise and emphasis on the method of analysis. Chapter 14 is a parallel effort for radar systems from the point of view of their overall functions and not their specific type. The last chapter in the book is an introduction to the field of electronic warfare, a rather controversial topic, presented here to illustrate the often conflicting goals of design and optimization.

I feel the entire book can be covered in one semester at the senior level, assuming the background materials in Chapters 2, 11, and 12 can be covered rapidly. If the students' backgrounds are not strong, a two-semester course is in order, filling in where necessary with material from the problems. In any event, the first ten chapters of the book are the absolute minimum that should be mastered by graduating Electrical Engineers before they enter the job market.

I have written this book the way I talk and lecture. I could, of course, claim the reason for this style is to make the book readable. But the real reason is that I read the following in the book *Palm Sunday* by Kurt Vonnegut, Jr., (1981): "Newspaper reporters and technical writers are trained to reveal almost nothing about themselves in their writings. This makes them freaks in the world of writers, since almost all the other ink-stained wretches in that world reveal a lot about themselves to readers. We call them revelations, accidental and intentional, elements of literary style."

After that *I knew* I had to write it as I speak. Maybe I resented the word "freak." Maybe deep down I harbored illusions of writing a technical book in literary style. Anyway, it turned out to be quite easy to let the writing flow as it came, and it came as it is presented in this book. At the end I realized that Mr. Vonnegut will always be right, at least about technical writers. There is not much you can put in about yourself when you are analyzing chirp radar—*accidental* or *intentional*. So I just hope the book is simply more readable.

Many thanks to Mrs. Niki Sarantoglu for typing the manuscript.

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CONTENTS

1

INTRODUCTION

Well-informed people know that it is impossible to transmit the voice over wires and that, were it possible to do so, the thing would be of no practical value.

A newspaper editor in 1865[1]

1.1 PROLEGOMENA

The oldest communication system is the person-to-person type, the one that operates when we talk to each other, transmitting messages back and forth by conversation. We, of course, had nothing to do with the development of this system; evolutionary forces are responsible for it, and the result is not yet well understood.

Like all systems, the person-to-person type has some difficulties, and many of them still remain uncorrected, as they appear to be caused by psychological factors. There was one difficulty, however—that of its inability to transmit messages over long distances, for which something could be done—and was. Fire, smoke, doves, and so on, quickly moved in to aleviate the problem and extend the range of this natural system. The origins of such primitive systems have been lost in antiquity. But crude as they may appear to us today, they were satisfactory for the human needs of their time. In fact, they had all the elements of a sound communication system, as will be seen during the discussion in the following section.

The first recorded instance of an artificial communication system has been found in the writings of the Greek historian Polivius[2] (201–120 B.C.). This system transmitted messages by using two groups of five torches, each group

[1] As reported by Alvin Toffler in *Future Shock* (New York: Random House, Inc., 1970).
[2] See Still (1946).

being placed on a wall 2 m high. Various combinations of torches in the two walls resulted in the codification of the 24 Greek letters and the blank that separates words from each other. Such walls were built in a way that messages could be carried over long distances—not very rapidly, of course, but faster than any other known method. It is worthwhile mentioning that this system is a pulse-code modulated system (PCM), and such systems are the latest word in modern communications, as we shall see in due time.

Modern communication systems are based on electricity and magnetism, and as such they probably owe their development in the discoveries of Oersted (1819) and Ampère (1820). This development has been phenomenal, most of it in the last 50 years. We now have transatlantic cables carrying voice messages across continents, satellites transmitting voice and picture messages across stars, and all these transmissions are dissipated in fractions of a second. Advances in basic science promise even faster developments for the future, developments that may change completely our presently known life-styles.

Radar systems, like communication systems, also have their origin in nature. Various animals (e.g., porpoises, bats) are known to have the ability to transmit acoustic waves and to obtain information about the outside world, by sensing their reflections (echoes). We, of course, are not a complete radar system but we certainly are half of one, the receiver half. Human beings cannot emit waves (although some people claim they can), but we can receive the reflection of waves emitted from other sources, and thus obtain information about the outside world. We do so, for example, every time we use our various senses (radar receivers). *Seeing* is accepting and analyzing optical reflections from objects. The only difference is that we do not emit the light waves to begin with, at least we did not, in the early part of our evolution. Nowadays, of course, we do, with a flashlight or other sources of optical waves, so that with a little ingenuity we have turned ourselves into a good radar system.

Extending our natural range as a radar system to greater distances did not start until the discovery of the telescope in the year 1608. But the telescope still did not have its own source of illumination, and depended mainly on the sun or other stars. Modern electromagnetic (or acoustic) radar differs in this important detail. It emits its own waves and then sits back to receive the return echoes and to analyze them. Its ability to sense the environment and obtain information about it has been extended to gigantic distances, sometimes millions of miles away. And it can do so in the dark, under cloud cover, under water, or various other adverse conditions that render other instruments inoperative.

Radar systems are more recent than communication systems. Although some of the principles of their operations were known earlier, the first radar systems appeared just before World War II. Since then, their development has been phenomenal. Despite the fact that their initial purpose was military (detecting enemy aircraft), radar systems are everywhere around us, in police (or passenger) vehicles, in ships, in airports, in weather stations, and in astronomical observatories. Their contributions to human well-being is steadily climbing. Knowledge of their principles of operation will soon become an integral part of the electrical engineering studies of undergraduates, and this is the reason for including them in this book.

Communication and radar systems are different, of course, particularly in the goals they wish to accomplish. Communication systems transmit information from one place to another. Radar systems are sensing devices. They send out a signal and they analyze the echo's changes from the original signal to deduce information about the object that reflected the signal. Despite this difference of purpose, their similarities are greater, and that is the reason they can be studied together in a unified manner. Both systems use signals for transmission, so signal theory is the common background for both. Both must convert this signal to electromagnetic waves by using devices that operate in the same manner. The waves travel through media that are similar in both cases. On the receiver side, both systems must receive a signal, usually contaminated by noise, and the information that it carries must be extracted. It should, therefore, be no surprise that a unified approach for analysis is available in both cases.

This first chapter is quite general in its approach. The first two of the sections that follow are devoted to each system separately, with the discussion from the overall systemic point of view. The third section compares the two, and points out their similarities and differences in some detail. The final section of the chapter reviews the approach and level of presentation of the contents of the entire book.

We should warn the reader that there are a lot of generalizations in the remainder of this chapter. This may be offensive, especially to the experts, as generalizations are *rarely* absolutely correct. Nevertheless, they have some merit, particularly in introducing a subject, a case in point in this, our first chapter. The idea here is to give an overall picture of the topics, a picture that readers must try to keep in the back of their minds or they may loose interest in the details that follow.

1.2 THE GENERAL COMMUNICATION SYSTEM

The purpose of a communication system is to transmit some piece of information from point A (the source) to point B (the destination). This goal is accomplished by a series of devices or systems interconnected in the manner shown in Fig. 1.2.1. This figure represents a very general communication system in block diagram form and as such, it is not very accurate or detailed. Nevertheless, it is satisfactory as an initial encounter with the system.

The signal $f(t)$ represents the information that needs to be transmitted. This $f(t)$ could be any number of things: a speech signal, a landscape photograph, the thoughts of a human being, the variations of temperature in the bottom of the sea, and so on. In most cases, this initial information signal can not be transmitted to the destinations in its "raw" form. For example, the thoughts of a human being cannot be transmitted directly to the brain of another

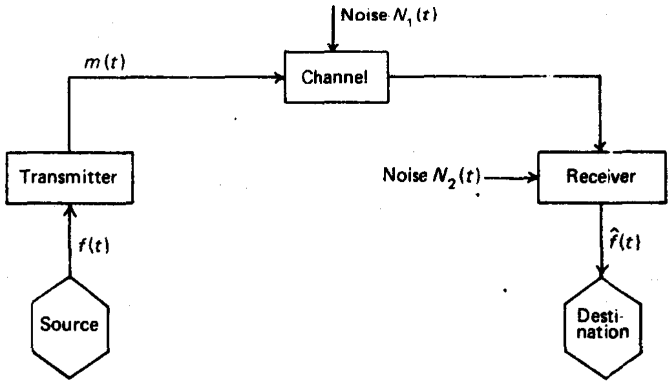

Figure 1.2.1 General communication system.

human being. They are not suitable for transmission as they are; they need some processing that will make them so. This processing is done by the system designated as the **transmitter** in the block diagram of Fig. 1.2.1.

The transmitter is therefore a device (or group of devices) whose function is to accept the raw $f(t)$ and turn it into a signal *that is suitable for transmission through the channel.* That, obviously, means that the transmitter (or the designer of the transmitter) must know the natures of $f(t)$ and channel, so that it makes the proper transformation. In the "human" communication system, the transmitter would include the organs and processes that transform the thoughts into a speech signal uttered by the mouth. The thoughts are transformed into acoustic waves, and these waves can travel through the channel, the air space between speaker and listener. Nature has, therefore, designed an excellent transmitter for this communication system, albeit only for short distances. For large distances, the acoustic waves of speech are not suitable for transmission. We have to come in and augment nature's work with electronic devices. Having discovered that electromagnetic waves (unlike sound waves) can travel great distances without much attenuation, we proceeded to develop an addition to nature's transmitter, which transforms the speech signal to an electromagnetic signal. In a radio communication system, the speech signal would, of course, be the raw $f(t)$, and the devices that transform it to an electromagnetic wave, the transmitter. In a television system, the raw $f(t)$ would be pictures and the transmitter would transform them into electromagnetic waves for wireless transmission or into electrical waves for cable transmission. The key words that obviously characterize the nature of the transmitter are the words "suitable for transmission through the channel."

Let us now consider the block designated as the **channel** in Fig. 1.2.1. This is defined as the transmission medium between transmitter and receiver. The most common type of channel is the atmosphere, that is, the air space between source and destination of information. Wire channels are also very popular, particularly in telephony or in computer-to-computer communication systems. In sonar the channel is water. In outer space communications (earth to other stars, earth to satellites, satellite to satellite, etc.) the channel is the atmosphere, free space, or both. Recently developed optical communication systems utilize channels made of plastic strands (fibers).

The channel is one of the key components of a communication system, because it is usually there and you are stuck with it. True, sometimes you can change it, but not without enormous costs in time and money. Channel changes for long-distance communications are very rare and occur once or twice in a person's lifetime, usually ushering new areas of civilization. Transatlantic cables were an example of a drastic channel change. Satellite communications can also be viewed as an example of such a change, although not a straightforward one. In both cases these new channels resulted in immense increases in the volume of information transmission between human beings. This had a profound effect on human civilization, an effect that is continuously being studied by humanists, as it is still not well understood.

So in most cases the channel is there and it is the transmitter that must be designed as the proper interface between it and $f(t)$. The channel must be studied well, so that the types of signals that it will permit to pass it must be ascertained. In fact, the channel presents us with more problems than that. It is there that we usually find the serious effects of noise [$N(t)$ in Fig. 1.2.1] for the first time. So it is not enough to know what signals can pass through the channel. You must also study the noise in the channel, for often, even though the signal goes through, it could be unrecognizable at the output of the channel.

The noise $N(t)$ usually comes as a package deal with the channel; that is, you are stuck with it as well. Noise can broadly be defined as a collection of signals that are undesirable and which distort the information signal during its passage through the channel. Usually, noise is caused by *unpredictable* natural phenomena, but not always. If you are trying to transmit information with smoke signals, for example, you would not do it in a dark night, for darkness (as noise) completely overshadows the signal. You might, however, try torches (or flashlights), which, in turn, would be useless during the daytime. These are both examples of predictable noise. Channels, however, more often than not contain unpredictable noises (electrical storms, outer space phenomena), and these must be studied well. Interestingly enough, such noises are not as unpredictable as they first appear. We will see toward the end of the book that they can be modeled mathematically in a manner that explains quite well their effects on the information signals that pass through the channel. So much for the channel, at least in this introductory presentation.

Let us now go to the other side of the communication system, the destination. There, we first encounter the block **receiver**. Generally speaking, the function of the receiver is to accept the signal that comes out of the channel and convert it back to its original form $f(t)$, or as is usually the case, $\hat{f}(t)$, which is