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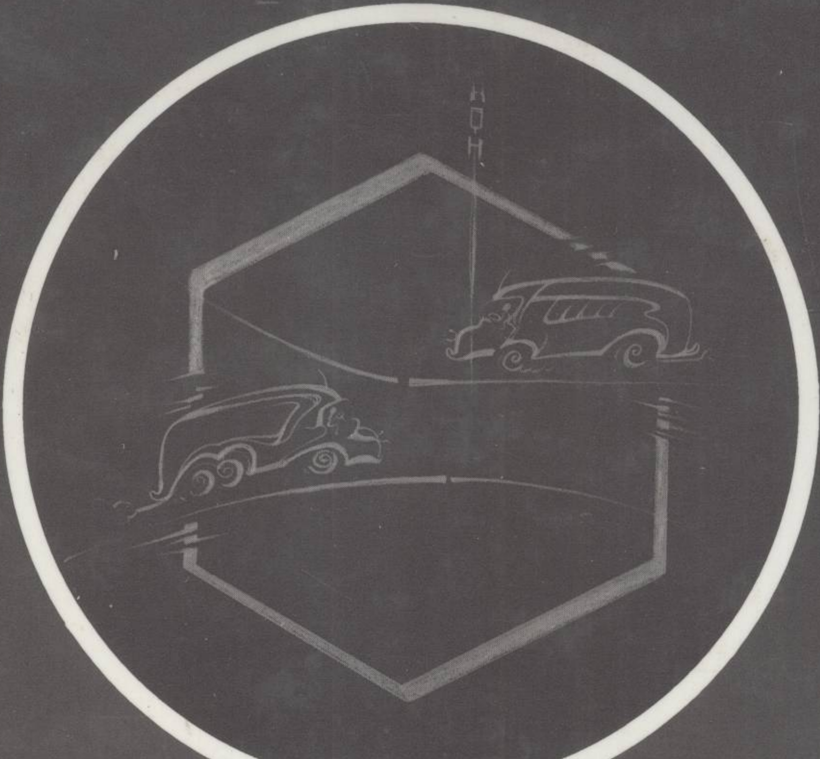

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Narrowband Land-Mobile Radio Networks

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Preface

Throughout history, the human race has shown a particular interest in communication. The demand for communication is closely related to mobility. Currently, a rapid growth of "mobile communication" has been seen, made feasible by recent technological developments. Mobile communication involves radio communication, in which at least one of the terminals can be in motion. Congestion of the radio frequencies allocated for mobile services requires highly efficient use of the electromagnetic spectrum.

Coverage

This book addresses the performance of mobile radio systems with narrowband radio channels. The term narrowband is used indicate that the transmission bandwidth is assumed to be relatively small compared to the coherence bandwidth of the radio channel. In particular, the effects of multipath fading and shadowing and of mutual interference between mobile users is investigated. To this end, the relevant propagation mechanisms are described initially, focusing on statistical channel models. For the planning of real systems, the suitability of some propagation models using terrain data is empirically evaluated. The statistical channel description is used to compute the performance of mobile radio links. Expressions are given for the outage probability and for the average duration of fades, taking into account mutual interference between users. A simplified model for the bit error rate in digital transmission is proposed, and numerical results are given for mobile telephone networks.

To study the performance of packet-switched mobile networks, the statistics of randomly arriving data packets are described for a number of access protocols. Using the assessed properties of physical radio links, the capacity of mobile data networks is computed, focusing on the spatial distribution of users over the service area. The network performance is calculated as a function of the distance between the mobile user and the fixed base station.

Methods are developed to find the effects of mutual interference between mobile terminals in a network of known dimensions. This allows selection of the most spectrum-efficient design that satisfies a prescribed network performance. Hence, the fundamental techniques presented in this book apply to spectrum-efficient spatial design and planning of infrastructures for mobile communication.

Acknowledgments

My interest in mobile radio communication was raised during my Ir. (M.Sc. E.E.) research project under the guidance of Dr. Jens C. Arnbak at Eindhoven University of Technology. This project has been the motivation for continuing my research at the Telecommunications and Traffic-Control Systems (T.V.S.) Group at Delft University of Technology, where I again enjoyed Dr. Arnbak's inspiring advice and support. This led to the completion my Ph.D. thesis, entitled "Effects of Fading and Interference in Narrowband Land-Mobile Networks," which was used as the basis for this book. I also greatly appreciated the numerous discussions with Dr. Ramjee Prasad, and I wish to thank him for the stimulating research environment he created. Further, I would like to thank Ir. Geert Awater, Ir. Adri Kegel, and the numerous students who in some way or another contributed to the contents of this book, particularly Hugo Goossen, Ramin Hekmat, Aart J.'t Jong, Pascal P.C. de Klerk, Kees van der Plas, Robert-Jan Venema, and John J.P. Werry.

The propagation experiments presented in Chapter 2 were obtained at the Physics and Electronics Laboratory F.E.L.-T.N.O., The Hague, in 1987 and 1988, where I benefited from the advice of Ir. Frank J.M. van Aken.

Modifications and additions to the original Ph.D thesis have been carried out at the University of California at Berkeley. I wish to acknowledge the discussions with my colleagues and graduate students, which significantly contributed to my insight and helped to improve the manuscript.

The cover and Figures 1.1 to 1.3, 1.6, 2.3 to 2.4, and 3.1 were drawn by my father, Martin Linnartz. It is with great pleasure that I include these pencil drawings, though not as a direct justification or visualization of the scientific results reported in this dissertation: an artist's interpretation, visualized in these drawings, fits the abstract and delimited characteristics of this introduction to theoretical analyses. By describing real-life systems with idealized, mathematical models and interpretations, scientific research appears to have clear analogies with the work of an artist. Both the artist and the researcher observe and analyze systems (natural or artificial) and formulate their own, modeled world. Despite all limitations, such models yield valuable insight into the system being investigated. To me, this is the most appealing aspect of scientific research.

It would have been impossible for me to complete this book without the support and friendship of all the others in The Netherlands and in California who contributed to making the preparation of this book an enjoyable time.

Jean-Paul Linnartz
Berkeley, California
June 1992

Contents

Chapter 1
Introduction

1.1 HISTORICAL SETTING

Communication systems using electrical and electronic technolgy have a significant impact on modern society. In early history, as the courier speeding from Marathon to Athens in 490 B.C. illustrates, information could be exchanged only by the physical transport of messages. Only a few examples exist of nonelectrical communication techniques for transfer of information via infrastructures other than those for physical transport: smoke signals, signal flags in maritime operations, and the semaphore, among others [1]. Early attempts to communicate visual signals by means of the semaphore, a pole with movable arms, were made in the 1830s in France. A similar experimental system was used by the Dutch during the "ten days campaign" against the Belgian revolt in 1831–1832. In 1837, the House of Representatives passed a resolution requesting the Secretary of the Treasury to investigate the feasibility of setting up such a system in the United States [2]. The market interest in enhanced communication systems was also clearly illustrated by the fact that in 1860 the Pony Express started regular physical message services over land in the U.S. At the same time, however, electronic systems for communication had started to develop.

*Tele*communication is defined by the *International Telecommunication Union* (ITU) as the transmission, emission, or reception of any signs, signals, or messages by electromagnetic systems [3]. The demonstration of (electrical) telegraphy by Joseph Henry and Samuel F.B. Morse in 1832 followed the discovery of electromagnetism by Hans Christian Ørsted and André-Marie Ampère early in the 1820s. In the 1840s, telegraph networks were built on the East Coast of the U.S. and in California. Rapid extension of their use followed; the first transatlantic cable was laid in 1858. In 1864, James Clerk Maxwell postulated wireless propagation, which was verified and demonstrated by Heinrich Hertz in 1880 and 1887, respectively. Marconi and Popov started experiments with the radio-telegraph shortly thereafter, and Marconi patented a complete wireless system in 1897. In 1876, Alexander Graham Bell patented the telephone. The invention of the diode by Fleming in 1904 and the triode by Lee de Forest in 1906 made possible rapid development of long-distance (radio) telephony. The invention of the transistor by Bardeen, Braittain, and Shockley, which later led to the development of integrated circuits, paved the way for miniaturization of electronic systems. The continued advances in microelectronic circuits have recently made the rapid development of mobile and personal communication systems feasible. Such systems offer person-to-person communication, giving freedom of movement for the users and, if desired, eliminating the ineffective calls experienced with the fixed telephony service when the user is away from his or her terminal. Moreover, new services, particularly those employing mobile *data* communication, are becoming feasible, such as *automatic vehicle location* (AVL) for fleet management, electronic mail, remote access to databases, vehicle printers, or automatic repetition of the messages if the driver has been away from the vehicle. Further, data communication makes encryption and data processing possible.

The effect of telecommunications on society at large [4, 5] may turn out to be as significant as the invention of the printing press, which initiated the changes in society in the sixteenth century and contributed to the end of feudalism [6, 7]. The introduction of new services, with due anticipation of their direct and indirect consequences, often requires conscious policies [8]. Nonetheless, user acceptance of new opportunities appears at least as important as political consensus. One discipline relevant to the understanding of the impact of the new developments, and thus also to formulating an information policy, whether liberal or more regulated, is the dynamic market theory [9]: each innovation has a critical period during its introduction. Case studies [10] indicate that the simultaneous introduction of a new service *and* a new technology has often failed in the past, notwithstanding any impressive advantages the new service would offer [8]. For instance, in many countries, except possibly in France, the introduction of videotex—a *new* service using a *new* technology—was not very successful. On the other hand, facsimile is a clear example of the successful introduction of a new service based on existing technology and an existing infrastructure, namely, the telephone network. Similarly, teletext offered a new service using existing transmitters for television broadcasting.

The successful introduction of the compact disk (CD) is an example of a new technology for an existing service previously offered by long-play records. Even the introduction of the electrical telegraph can be interpreted as an improved technological solution to a service pioneered by the semaphore and the Pony Express service. As the concurrent experiments with semaphore communication show, the electrical telegraph was thus not a purely technology-push development: a clear interest (market pull) in communication to bridge physical distances was present. The acceptance of these innovations came about as a novel and better technical implementation of a service previously offered with inferior techniques.

In the 1980s, we have seen a very successful innovation of the existing telephone service: cellular radio. Further technological advances in mobile communication are developed apace, while experiments with new services and applications are also performed with currently known, mature, though sometimes inadequate, technology. Examples of the latter range from the not very successful experiments with mobile data services using wireline telephone modems over cellular voice channels, to exchanging routine information (e.g., about traffic jams) in spoken form. However, such pilot systems and experiments appear to be indispensable. Introduction of new technologies and infrastructures such as packet-switching (store-and-forward) mobile data networks may only be profitable and justifiable once experimental systems prove their usefulness to potential users and are accepted by them.

The main body of this book addresses some of the technical problems experienced in designing new systems for mobile (voice and data) communication. The aspect of mobility related to communication will be discussed in the next section.

1.2 COMMUNICATION AND MOBILITY

Evident in early history is the economic relation between mobility, trade, and transport on the one hand, and exchange of information on the other. Shortly after the first coins were minted in Lydia in the seventh century B.C., professional currency exchange was made by the many monetary sovereignties at the important commercial crossroads [11]. Doing business at crossroads ensured not only a continuous stream of clients, but also information from all relevant parts of the ancient trading world.

The first news-gathering services were established by the Medici, Fugger, and Welser families, who set up their own messenger services to assist cross-border commercial operations. Ships and gazettes reported on wars, crop failures, gold finds or natural catastrophes in foreign territories. In the seventeenth century, Louis Elsevier located the Copenhagen offices of his book printers and sellers company in the local Stock Exchange, which ensured rapid communication with international partners. Here, the novel newspaper *Amsterdam Corantos* was available, with the most up-to-date news items, exchange rates, and commodity values collected worldwide by crews of the Dutch merchant fleet. The fleet of ships transported not only goods, including printed matter and maps, but also business information and newly discovered topographical data. Thus, shipping activities not only *distributed* information (e.g., in printed form), they also *contributed* information [12]. The very combination of these two information services allowed countries like Holland to develop into important international trading nodes during the first part of the seventeenth century. This historical example illustrates that information was originally communicated via the infrastructure for physical transport (see Figure 1.1), and that information was merely transferred between locations of human activities, such as cities.

With the advent of telecommunications, the spatial relationship between information and physical transport changed dramatically. In the early telegraph systems, the origination and destination of information traffic continued to be mainly determined by the existing locations of human activities. However, although messages were still mostly sent from city to city, they no longer used media primarily