PREFACE

Regardless of the branch of science or engineering, theoreticians have always been enamored with the notion of expressing their results in the form of closed-form expressions. Quite often the elegance of the closed-form solution is overshadowed by the complexity of its form and the difficulty in evaluating it numerically. In such instances, one becomes motivated to search instead for a solution that is simple in form and likewise simple to evaluate. A further motivation is that the method used to derive these alternative simple forms should also be applicable in situations where closed-form solutions are ordinarily unobtainable. The search for and ability to find such a unified approach for problems dealing with the evaluation of the performance of digital communication over generalized fading channels is what provided the impetus to write this textbook, the result of which represents the backbone for the material contained within its pages.

For at least four decades, researchers have studied problems of this type and system engineers have used the theoretical and numerical results reported in the literature to guide the design of their systems. While the results from the earlier years dealt mainly with simple channel models, such as Rayleigh or Rician multipath fading, the applications in more recent years have become increasingly sophisticated, thereby requiring more complex models and improved diversity techniques. Along with the complexity of the channel model comes the complexity of the analytical solution that enables one to assess performance. With the mathematical tools that were previously available, the solutions to such problems when possible had to be expressed in complicated mathematical form that provided little insight into the dependence of the performance on the system parameters. Surprisingly enough, not until 1998 had anyone demonstrated a unified approach that not only allows previously obtained complicated results to be simplified both analytically and computationally but also permits new results to be obtained for special cases that heretofore resisted solution in a simple form. This approach was first introduced to the public by the authors in a tutorial-style article that appeared in the September 1998 issue of the *IEEE Proceedings*. Since that time, it has spawned a large wave of publications on the subject in the technical journal and conference literature, by both the authors and many others and, based on the variety of applications to which it has already been applied, will no doubt continue well into the new millennium. The key to the success of this approach relies on employing alternative representations of classic functions arising in the error probability analysis of digital communication systems (e.g., the Gaussian Q-function[1] and the Marcum Q-function) in such a manner that the resulting expressions for various performance measures such as average bit or symbol error rate are in a form that is rarely more complicated than a single integral with finite limits and an integrand composed of elementary (e.g., exponential and trigonometric) functions. By virtue of replacing the conventional forms of the above-mentioned functions by their alternative representations, the integrand will contain the moment generating function (MGF) of the instantaneous fading SNR, and as such the unified approach is referred to as the *MGF-based approach.*

The first edition of this book was aimed at collecting and documenting the huge compendium of results contained in the myriad of contributions developed from the MGF-based approach that had been reported until that time and, by virtue of its unified notation and collocation in a single publication, would thereby be useful to both students and researchers in the field. In 1999 the manuscript for the first edition was submitted to the publisher. Since that time, a great deal of additional significant work on the subject has been performed and reported on in the literature, so much so that a second edition of the book is warranted and will be extremely beneficial to these same researchers and students in bringing them up to date on these new developments.

Perhaps the most significant of these new developments is the explosion of interest and research that has taken place in the area of transmit diversity and space-time coding and the associated multiple-input/multiple-output (MIMO) channel, a subject that was briefly alluded to but not discussed in any detail in the first edition. One of the key elements of the second edition is a comprehensive chapter on this all-important subject that, in keeping with the main theme of the book, deals with the performance evaluation aspects of such systems. The performance of MIMO systems is also treated from other perspectives elsewhere in the text.

Aside from these developments, many new and exciting results have been developed by the authors as well as other researchers that (1) have led to new and improved diversity schemes and (2) allow for the performance analysis of previously known schemes operating in new and different fading scenarios not discussed in the first edition. A few of these developments are (1) new alternative forms for classic mathematical functions such as the second-order Gaussian Q-function and also higher powers of the first-order Gaussian Q-function; (2) improved diversity schemes such as threshold and postdetection generalized selection combining, switch-and-examine combining, and switch-and-wait combining; (3) new channel fading models of interest in wireless and mobile applications; (4) new bounds on system performance in the presence of fading; and (5) new mathematical results

[1]The Gaussian Q-function $Q(x)$ has a one-to-one mapping with the complementary error function [i.e., $Q(x) = \frac{1}{2}\text{erfc}\left(x/\sqrt{2}\right)$] commonly found in standard mathematical tabulations. In much of the engineering literature, however, the two functions are used interchangeably, and as a matter of convenience we shall do the same in this book.

related to quadratic forms in Gaussian random variables and the difference in chi-square random variables with different degrees of freedom, allowing for the analysis of practical communication performance measures such as the outage probability of digital communication systems in the presence of multiple interferers. In fact, because of the importance of the latter issue in multiuser communication systems, a new chapter has been added on this subject. The list above is only a small sample of the voluminous amount of material (on the order of several hundred pages) that has been added to the second edition.

As in the first edition, in dealing with the application of the MGF-based approach, the coverage in this edition of the book is extremely broad in that coherent, differentially coherent, partially coherent, and noncoherent communication systems are all handled as well as a large variety of fading channel models typical of communication links of practical interest. Both single- and multichannel reception are discussed, and in the case of the latter, a large variety of diversity types are considered. In fact, the chapter on multichannel reception (Chapter 9) is by itself now over 325 manuscript pages long and, in reality, could stand alone as its own textbook. For each combination of communication (modulation/detection) type, channel fading model, and diversity type, expressions for various system performance measures are obtained in a form that can be readily evaluated.[2] All cases considered correspond to real practical channels, and in many instances the closed-form expressions obtained can be evaluated numerically on a handheld calculator.

In writing this book, our intent was to spend as little space as possible duplicating material dealing with basic digital communication theory and system performance evaluation that is well documented in many fine textbooks on the subject. Rather, this book serves to advance the material found in these texts and as such is of most value to those desiring to extend their knowledge beyond what ordinarily might be covered in the classroom. In this regard, the book should have a strong appeal to graduate students doing research in the field of digital communications over fading channels as well as practicing engineers who are responsible for the design and performance evaluation of such systems. With regard to the latter, the book contains copious numerical evaluations that are illustrated in the form of parametric performance curves (e.g., average error probability versus average signal-to-noise ratio). The applications chosen for the numerical illustrations correspond to practical systems and as such the performance curves provided will have far more than academic value. The availability of such a large collection of system performance curves in a single compilation allows researchers and system designers to perform tradeoff studies among the various communication type/fading channel combinations so as to determine the optimum choice in the face of their available constraints.

The structure of the book is composed of five parts, each with its own express purpose. The first part contains an introduction to the subject of communication system performance evaluation followed by discussions of the various types of fading channel models and modulation/detection schemes that together form the

[2]The terms *bit error probability* (BEP) and *symbol error probability* (SEP) are quite often used as alternatives to *bit error rate* (BER) and *symbol error rate* (SER). With no loss in generality, we shall employ both usages in this text.

overall system. Part 2 starts by introducing the alternative forms of the classic functions mentioned above and then proceeds to show how these forms can be used to (1) evaluate certain integrals characteristic of communication system error probability performance and (2) find new representations for certain probability density and distribution functions typical of correlated fading applications. Part 3 is the "heart and soul" of the book since, in keeping with its title, the primary focus of this part is on performance evaluation of the various types of fading channel models and modulation/detection schemes introduced in Part 1 both for single and multichannel (diversity) reception. Before presenting this comprehensive performance evaluation study, however, Part 3 begins by deriving the optimum receiver structures corresponding to a variety of combinations concerning the knowledge or lack thereof of the fading parameters: amplitude, phase, and delay. Several of these structures might be deemed as too complex to implement in practice; nevertheless, their performance serves as a benchmark against which many suboptimum but practical structures discussed in the remainder of the chapter might be compared. Part 4, which deals with multiuser communications, considers first the problem of outage probability evaluation followed by optimum combining (diversity) in the presence of cochannel interference. The unified approach is then applied to studying the performance of single- and multiple-carrier direct-sequence code-division multiple-access (DS-CDMA) systems typical of the current digital cellular wireless standard. Part 5 extends the theory developed in the previous parts for uncoded communication to error-correction-coded systems and then space-time-coded systems and concludes with a discussion of the capacity of fading channels.

Whereas the first edition has already established itself as the classic reference text on the subject with no apparent competition in sight, it is a safe bet that the second edition will continue to maintain that reputation for years to come. The authors know of no other textbook currently on the market that addresses the subject of digital communication over fading channels in as comprehensive and unified a manner as is done herein. In fact, prior to the publication of this book, to the authors' best knowledge there existed only two works (the textbook by Kennedy [1] and the reprint book by Brayer [2]) that, like our book, are totally dedicated to this subject, and both them are more than a quarter of a century old. While a number of other textbooks [3–11] devote part of their contents[3] to fading channel performance evaluation, by comparison with our book, the treatment is brief and as such is incomplete. Because of this, we believe that our textbook is unique in the field.

By way of acknowledgment, the authors wish to express their personal thanks to Dr. Payman Arabshahi of the Jet Propulsion Laboratory, Pasadena, CA for providing his invaluable help and consultation in preparing the submitted electronic version of the manuscript. Mohamed-Slim Alouini would also like to also like to express his sincere acknowledgment and gratitude to his PhD advisor Prof. Andrea J. Goldsmith of Stanford University, Palo Alto, CA for her guidance, support, and constant encouragement. Some of the material presented in Chapters 9,

[3]Although Ref: 11 is a book that is entirely devoted to digital communication over fading channels, the focus is on error-correction-coded modulation and therefore would relate primarily only to Chapter 13 of our book.