

THE BEST *of* THE BEST

**Fifty Years of Communications and
Networking Research**

Edited by

WILLIAM H. TRANTER

DESMOND P. TAYLOR

RODGER E. ZIEMER

NICHOLAS F. MAXEMCHUK

JON W. MARK



**IEEE
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The Best of the Best

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William H. Tranter
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Preface

The year 2002 marked the fiftieth anniversary of the founding of the IEEE Communications Society. Various special events (two Grand Reunions at IEEE ICC 2002 in New York and IEEE GLOBEOM 2002 in Taipei) took place to celebrate this significant milestone. A number of publications were part of this celebration. For example, the *IEEE Communications Magazine, 50th Anniversary Issue*, was published in May 2002. The Society issued a 2 DVD compilation of 28,000 papers, *Communications Engineering Technology; A Comprehensive Collection of Papers 1953-2001*, and a 128-page volume *A Brief History of Communications*. Another activity, focusing on archival research papers was a compilation of outstanding papers that have appeared in the Society's transactions and journals during the past five decades. These papers represent a selection of various key research papers that have been published by the Communications Society. Moreover, they provide a snapshot history of the evolution of communications systems over this five-decade period. This compilation was known as the "Best of the Best" and was distributed via the web page of the IEEE Communications Society, and was also distributed at Communications Society conferences and other appropriate events during 2002. This volume is at long last a hard copy edition of this compilation.

The editors fully realize that there will not be unanimous agreement that the chosen papers represent the best possible selection and that a list of "best papers," like beauty, is in the eye of the beholder. We certainly agree that many excellent papers have appeared in the publications of the Communications Society that are not included in this publication. In order to select the papers included here the editors attempted to put in place a process that would result in a useful reference, represent a good cross section of the best papers, and provide a historical perspective of the development of communications over the past fifty years.

It should be pointed out that the papers included herein represent the best of "our" best with our referring to the IEEE Communications Society. The journals represented include the *IRE Transactions on Communications Systems*, the *IEEE Transactions on Communications Technology*, the *IEEE Transactions on Communications*, the *IEEE Journal on Selected Areas in Communications*, and the *IEEE/ACM Transactions on Networking*. We should point out that two additional publications focusing on research results have recently joined the suite of Communications Society publications: *IEEE Communications Letters* and the *IEEE Transactions on Wireless Communications*. There are a number of journals that publish research-level papers in communications that are not part of the IEEE Communications Society and are therefore not represented here. The *IEEE Transactions on Information Theory* and special issues of the *Proceedings of the IEEE* devoted to communications are of particular note as are several publications of the IEE (Institution of Electrical Engineers, now the IET).

The volume has two major sections. The first section contains 41 papers dealing with physical and link layer aspects of communications. These papers are arranged chronologically within the section. The second section consists of 16 network papers that deal with the higher layers in communications systems. This second set of papers was compiled by a second set of guest editors, whose expertise lies in the networks and protocols area. They, too, are arranged in chronological order within the section.

Selection Process for the Physical and Link Layer Communications Papers

As the first step in the process of choosing the physical and link layer papers, the editors compiled a preliminary list of 26 papers dealing with physical and link layer communications. The initial list was developed from a list of those papers receiving the most citations and those papers receiving "best paper" awards. Also included on the list were candidate papers based on our experience as Transactions and Journal editors and as members of the research community. The next step was to circulate this preliminary list to 43 members of the Communications Society who had extensive service as editors of various IEEE Communications Society publications or as leaders in the research community. This group was asked to respond to the preliminary list and suggest additions or deletions along with the reasons for their suggestions. After considering the inputs received, the list was expanded from 26 to the 41 papers appearing in this book. It is significant that only 17 of the initially selected 26

papers survived this review process. It is clear from this statistic that the reviewers took their jobs seriously and we thank them for their efforts and for their support of this project. The names of these reviewers appear in Supplement A of this introduction.

Selection Process for the Networking Papers

The selection of papers in the networking area was a bit more free-form than in the physical layer communications area. In May 2001, invitations were sent to 159 members of the networking community to nominate two or three papers, other than their own, that most affected their own work. The nominators were asked to briefly indicate why they considered the papers important. While a large number of very good papers received nominations, a set of 16 papers dominated. Those papers are presented in this issue.

The only constraint that we placed on the nominations was that they appeared in one of the IEEE Communications Society's three archival journals, the *IEEE Transactions on Communications*, the *IEEE Journal on Selected Areas in Communications*, or the *IEEE/ACM Transactions on Networking*. Networking, to a much greater extent than physical communications, is also in the domain of several other societies, and many important publications in networking are not in this list because they appeared in a journal of one of our sister societies or in one of the many conferences in this area.

If you count the number of papers you will note that 56 papers appear, not 57. This is because one paper "The Throughput of Packet Broadcasting Channels" by Norman Abramson was selected for both sections.

The Past Few Years

The initial plan was to publish this volume in 2002. However, due to a number of reasons this did not prove practical. Now, through a partnership of the IEEE Press and John Wiley, publication has been made possible.

Since several years have passed between the original submissions of the most recent papers appearing here, the editors considered a method for updating this volume. All of our research publications sponsor a best paper award and it was decided to list the recipients of these awards given in 2000-2005 within this introduction. These papers appear in Supplement B of this introduction. A complete list of recent (1994-2005 for most journals) awards can be found on the Communications Society home page appearing at

<http://www.comsoc.org/socstr/org/operation/awards/paperawards.html/>

A Brief Perspective on Communications

In order to place the papers in this volume in perspective we provide a brief outline of the development of communications here and of the IEEE Communications Society in the next section. Much of what follows in this section and the next is based on *A Brief History of Communications*, which was published by the IEEE Communications Society as a part of the 50th anniversary events. The material in this booklet is available on the web site of the IEEE History Center along with lists of publications and extensive related material. The URL for the IEEE History Center is

http://www.ieee.org/web/aboutus/history_center/

The interested reader is encouraged to consult this site for additional perspectives on the history of electrical engineering, including communications, and on the history of the IEEE Communications Society.

Although the first 50 years of the IEEE Communications Society spans the period (1952-2002) many agree that the period of "modern" communications has its roots in 1947. The year 1947 was a benchmark year for the communications industry and was marked by two events which, at the time, were not viewed as closely related. The first of these events was the publication of the seminal paper *A Mathematical Theory of Communications*, by Claude Shannon. This paper quantitatively defined information in the communications context and established fundamental limits on the performance of communication systems. The concepts of source coding and channel (error-correction) coding have their roots in this paper, as does the field of information theory. Without the contributions of information theory, and error-correction coding in particular, modern communication systems, which are often required to perform well in heavy interference and noise environments, would simply not exist. The second event of 1947 was the invention of the point-contact transistor by Shockley, Bardeen, and Brattain. The transistor led to the integrated circuit and microelectronics. Microelectronics enabled the development of many communication devices rang-

ing from CD and DVD players, to cell phones and satellite communication systems. Microelectronics also made possible the development of high-speed desktop computers at reasonable cost and this enabled the development of computer communication networks culminating in today's internet. It should be pointed out that both of these events were products of research performed at Bell Laboratories.

This is not to say that important strides in the fields of communications were not made prior to 1947. Indeed the early days of communications (pre 1947 in this context) saw the development of much of the basic theory of electrical circuits, electronics, and electromagnetics that led to the invention of the telegraph, telephone, AM and FM radio, and television. Few today realize that the first working transatlantic telegraph cable was laid in 1857-1858, approximately 150 years ago. The now famous 1928 paper by Nyquist developed many of the concepts required to design modern, high-speed data communications systems for band-limited channels. The late 1930's and early 1940's also saw the invention of radar initially by the British. Radar systems were among the first communication systems to utilize the "modern" tools of statistical communication theory. The time between World War II and 1952 was dominated by the further development of both radio and television.

Plans for an undersea telephone cable were initially formulated in 1952 between Bell Telephone and the British Post Office. This cable, connecting the US and the UK, was installed in 1955 and 1956. Known as TAT1, this cable successfully operated from 1956 to 1979. A number of other telephone cables followed, notably cables from France and Newfoundland (TAT-2), Alaska to Washington state, and Hawaii to California. It should be recalled that undersea telephone cables were preceded by undersea telegraph cables by 100 years!

The next revolution in transcontinental communications was provided by the communications satellite. The first artificial earth satellite, Sputnik, was successfully launched in October 1957, by the Soviet Union. This was followed a few months later by the first successful US satellite, Explorer I. By the end of the 1950's, the enabling technologies required for commercial satellite communications were in place. The first communications satellite, Echo I, was launched in August, 1960. Echo I was a passive satellite in which signals were bounced off the surface of the satellite. While Echo I demonstrated the viability of satellite communications, very high transmitter power was required to overcome path losses. The answer to this problem was, of course, active satellites capable of receiving and retransmitting signals using high-gain antennas.

The first active communications satellites, Telstar I and Telstar II, were launched in 1962 and 1963, respectively. In addition to telephone channels, Telstar II provided one television channel. These were not commercial systems but were developed to demonstrate the viability of satellite communications systems. In 1964 INTELSAT, an organization involving the communications agencies of over 100 countries, was formed as an international body to develop and operate the global satellite communications system. INTELSAT deployed four generations of satellite systems operating in geosynchronous orbit. Telstar and INTELSAT provided the basic building blocks for modern satellite-based communications providing intercontinental telephone and television relaying, subscription television and radio, global positioning systems (GPS), and a host of other services.

Another significant advance in high-speed communications was the development of optical fiber systems in the late 1960s. The two enabling technologies were the invention of the laser in 1959-60 and the development of the glass fiber waveguide by Kao and Hockham in 1966. The first field installation of an optical fiber system using a semiconductor laser took place in the mid 1970s.

Two additional developments of the past three decades changed the way we use and view communications. These two developments were the computer network and the wireless cellular system. These two developments gave rise to intense research activity. This research activity continues to this day and gave rise to two research journals published by the IEEE Communications Society. These are the *IEEE/ACM Transactions on Networking*, focusing on computer communications, and the *IEEE Transactions on Wireless Communication*, focusing on wireless systems.

Although the ARPANET was not the first computer network to be demonstrated, the ARPANET was the first network to use packet switching and is considered by most to be the first network having long-term significance. The development of the ARPANET was funded by the Advanced Research Projects Agency (ARPA), an arm of the U.S. Department of Defense. The ARPANET was based on the seminal research of Kleinrock, Baran, and Davies and connected a number of universities and research laboratories in the U.S. ARPANET, despite its capabilities, was not widely used until Robert Kahn demonstrated ARPANET capabilities in 1972 at the first International Conference on Computer Communications. Also in 1972, Packet Communications, Inc., was formed to market communications services along the lines of the ARPANET model. The first major result of this initiative was Telnex, which served seven U.S. cities in 1975.

The work of Robert Kahn and Vinton Cerf, along with many other researchers, was instrumental in transforming the ARPANET into what we know today as the Internet, which is a network of networks. Cerf and Kahn proposed the Internet architecture which, because of its flexibility and decentralized nature, was able to accommodate a wide range of users and applications. They developed the host-to-host protocol and the Internet protocol (TCP/IP) which was fundamental in supporting the growth of the Internet. In addition, the 1980s saw the personal computer gaining a place both in the home and on the office desktop and this rapid expansion of computer access gave the masses network accessibility. Today the Internet, coupled with a wide variety of supporting software, such as web browsers and search engines, supplies a variety

of services including email, information processing, voice and video transmission, as well as applications to education and entertainment.

Wireless cellular communications, like the Internet, has witnessed recent explosive growth. Much of the fundamental research leading to wireless cellular communications was performed at Bell Laboratories in the 1960s and a series of papers focused on this research was published in the *Bell Systems Technical Journal*. The cellular concept was proposed to the FCC in 1968. At this time much of the theory was in place and by 1980, the hardware necessary for the practical implementation of wireless cellular systems was available. In 1983 the FCC allocated spectrum for wireless services in the 800 MHz frequency band. Later that year the first wireless cellular system was deployed by Ameritech in Chicago, IL. From this beginning the wireless industry grew at an exponential rate worldwide. Wireless communications has brought telephone service to many people living in environments where wired telephone service is simply impractical and in many countries the number of cell phones significantly exceeds the number of wired phones. Much of the current research is aimed at improving the quality of service, increasing bandwidth, and developing new services for the user.

Hopefully this brief perspective helps place the papers in this book in historical perspective and provides insight into the exciting nature of the communications industry.

A Brief Perspective on the IEEE Communications Society

The IEEE Communications Society, like all of the IEEE, has its roots in the AIEE (American Institute of Electrical Engineers) and the IRE (Institute of Radio Engineers). The older of these two institutes, the AIEE, dates back to 1884 and, at least early in the history of the AIEE, had a focus on telegraph and telephone. This focus, however, soon shifted to electric power generation and distribution. In order to maintain technical diversity a number of Special Committees were organized. A Committee on Telegraphy and Telephony was formed in 1903. In 1915 the Special Committees were renamed Technical Committees. This put in place the technical committee structure that lives to this day.

The Institute of Radio Engineers (IRE) was formed in 1912 by engineers wishing to have a technical institute focusing on wireless radio transmission and the related electronics. In 1937, the IRE formed a technical committee structure with the first six committees named broadcast, electroacoustics, radio receiving, television and facsimile, transmitting and antennas, and wave propagation. The IRE grew rapidly and there was considerable competition between the AIEE and the IRE for members. As a result, between 1950 and 1960 the AIEE formed a number of technical committees focusing on communications, including technical committees on television broadcasting, communication theory, data communication, and space communication. In 1952, the IRE Professional Group on Radio Communications was formed and later that year was renamed the IRE Professional Group on Communications Systems. This semi-autonomous group grew rapidly, formed a series of technical conferences, and initiated publication of the *IRE Transactions on Communications Systems*. This publication was the forerunner of the *IEEE Transactions on Communications*.

The formation of the IRE Professional Group on Communications Systems in 1952 marks Year 1 of the 50-year history spanned by this collection of technical papers. It should be noted that three papers in this collection by Costas (March 1957), Hancock and Lucky (December 1960), Arthurs and Dym (December 1962), and Prosser (December 1962) were originally published in the *IRE Transactions on Communications Systems*. When the AIEE and the IRE formally merged in 1963 the *IRE Transactions on Communications Systems* was renamed the *IEEE Transactions on Communications Systems* and two papers in this volume by Bello (December 1963), and Baran (March 1964) were originally published in the *IEEE Transactions on Communications Systems*. In 1964 the IEEE Group on Communications Technology was formed, basically from the IRE Professional Group Communications Systems. The *IEEE Transactions* was renamed the *IEEE Transactions on Communications Technology*, as the papers in this volume published between 1964 and 1971 indicate. When the IEEE Communications Society was formed in 1972 the *IEEE Transactions on Communications Technology* became the *IEEE Transactions on Communications* and retains this name to this day.

Thus, in a real sense, the *IRE Transactions on Communications Systems*, the *IEEE Transactions on Communications Systems*, the *IEEE Transactions on Communications Technology*, and finally the *IEEE Transactions on Communications* all represent the same journal, which changed names from time-to-time because of a merger and several reorganizations. The organizational structure and many of the volunteers which led these publications changed little from year-to-year although the number of papers published experienced tremendous growth. The influence of the four technical journals on the field of communications has been tremendous and represents a history of research performed in the field of communications. This is evidenced by the fact that 45 of the 56 papers in this volume come from these four journals.

As the IEEE Communications Society matured and the field became broader several new journals were added. The *IEEE Journal on Selected Areas in Communications* began publication in 1983 to serve as a journal focusing on single topics of emerging research interest. Prior to 1983, the *Transactions on Communications* published special issues when the need was apparent. Note that 10 papers in this volume were originally published in the *IEEE Journal on Selected Areas in Communica-*

tions. In 1993, publication of the *IEEE/ACM Transactions on Networking* was initiated to serve the rapidly advancing networking field. Two papers in this volume are from that publication. Two new research journals were recently added to the ComSoc's suite of archival research journals, namely *IEEE Communications Letters* and *IEEE Transactions on Wireless Communications*, but they are too new for papers published in these two journals to be represented here.

Dedication

We trust that you, the reader, will find this volume to be a useful reference in your further work in communications and that it will serve also to provide you with a historical perspective on the development of modern communications systems. We hope that students who browse this volume will be inspired by the work represented by the papers contained herein, will receive a sense of the excitement and opportunities represented within the communications industry, and will be motivated to make their own contributions to the field. Finally, we hope that you will find the volume to be a useful reminder of the fiftieth anniversary of the Communications Society and that it will serve as an indication of the many problems that remain to be solved in the worldwide communications systems research and development scene. We dedicate this volume to those who have advanced the field of communications over the past half century. The editors thank the many people who contributed to the development of this volume and to the authors of the outstanding papers contained herein. Without these contributions this volume would not have been possible.

Acknowledgement

Planning for the the 50th anniversary of the IEEE Communications Society began in 1998 with The Fiftieth Anniversary Advisory Board (FAAB) chaired by Jack McDonald. Their recommendations were accepted by the BOG in 1999 and the 50th Anniversary Implementation Committee was formed. Members included Celia Desmond, Roberto de Marca, Harvey Freeman, Jack McDonald, Tom Plevyak, Curtis Siller, and Jack Howell.

The IEEE History Center at Rutgers University researched and wrote a short history of the technology which was subsequently published by the IEEE Communications Society in a small paperback "A Brief History of Communications Technology." The editors want to acknowledge the efforts of David Hochfelder, David Morton, William Aspray, Andrew Goldstein, and Robert Colburn of the History Center and Chip Larkin of AT&T. Additional thanks go to Amos Joel for preparing and compiling much of the information regarding the history of the society. Substantial parts of the Preface of "The Best of the Best" have been based on "A Brief History of Communications Technology."

The editors also wish to thank Communications Society President Nim Cheung for his efforts to support the print version of "The Best of the Best."

For Physical and Link Layer Communications

William H. Tranter
Desmond P. Taylor
Rodger E. Ziemer

For Networking

Nick Maxemchuk
Jon Mark

Preface Supplement A—Reviewers for Physical and Link Layer Communications

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Gordon Stuber	Gottfried Ungerboeck	Reinaldo A. Valenzuela
Sergio Verdu	Andrew J. Viterbi	Steven B. Weinstein
Stephen B. Wicker		

Preface Supplement B—Recent Award Winning Papers Appearing in Research Journals Published by the IEEE Communications Society

The Leonard G. Abraham Prize Paper Award is presented annually to the best paper published in the *IEEE Journal on Selected Areas in Communications*.

Tai-Ann Chen, M. P. Fitz, Wen-Yi Kuo, M. D. Zoltowski, and H. Grimm, “A Space-Time Model for Frequency Nonselective Rayleigh Fading Channels with Applications to Space-Time Modems,” *IEEE Journal on Selected Areas in Communications*, Vol. 18, No. 7, pp. 1175-1190, July 2000.

R. R. Müller, and S. Verdù, “Design and Analysis of Low-Complexity Interference Mitigation on Vector Channels,” *IEEE Journal on Selected Areas in Communications*, Vol. 19, No. 8, pp 1429-1441, August 2001.

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**PHYSICAL AND
LINK LAYER ASPECTS
OF COMMUNICATIONS**

Turbo Space–Time Processing to Improve Wireless Channel Capacity

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Abstract—By deriving a generalized Shannon capacity formula for multiple-input, multiple-output Rayleigh fading channels, and by suggesting a layered space–time architecture concept that attains a tight lower bound on the capacity achievable, Foschini has shown a potential enormous increase in the information capacity of a wireless system employing multiple-element antenna arrays at both the transmitter and receiver. The layered space–time architecture allows signal processing complexity to grow linearly, rather than exponentially, with the promised capacity increase. This paper includes two important contributions: First, we show that Foschini’s lower bound is, in fact, the Shannon bound when the output signal-to-noise ratio (SNR) of the space–time processing in each layer is represented by the corresponding “matched filter” bound. This proves the optimality of the layered space–time concept. Second, we present an embodiment of this concept for a coded system operating at a low average SNR and in the presence of possible intersymbol interference. This embodiment utilizes the already advanced space–time filtering, coding and turbo processing techniques to provide yet a practical solution to the processing needed. Performance results are provided for quasi-static Rayleigh fading channels with no channel estimation errors. We see for the first time that the Shannon capacity for wireless communications can be both *increased* by N times (where N is the number of the antenna elements at the transmitter and receiver) and *achieved* within about 3 dB in average SNR, about 2 dB of which is a loss due to the practical coding scheme we assume—the layered space–time processing itself is nearly information-lossless!

Index Terms—Equalization, interference suppression, space–time processing, turbo processing.

I. INTRODUCTION

TURBO” and “space–time” are two of the most explored concepts in modern-day communication theory and wireless research. From a communication theorist’s viewpoint, “turbo” coding/processing is a way to approach the Shannon limit on channel capacity, while “space–time” processing is a way to increase the possible capacity by exploiting the rich multipath nature of fading wireless environments. We will see through a specific embodiment in this paper that combining the two concepts provides even a practical way to both increase and approach the possible wireless channel capacity.

With growing bit rate demand in wireless communications, it is especially important to use the spectral resource efficiently.

The basic information theory results reported by Foschini and Gans [1] have promised extremely high spectral efficiencies possible through multiple-element antenna array technology. In high scattering wireless environments (e.g., troposcatter, cellular, and indoor radio), the use of multiple spatially separated and/or differently polarized antennas at the receiver has been very effective in providing diversity against fading [2], [3]. Receiver diversity techniques also create signal processing opportunities for interference suppression and equalization (e.g., [4]–[6]). However, using multiple antennas at either the transmitter or the receiver does not enable a significant gain in the possible channel capacity. According to [1], the Shannon capacity for a system with 1 transmit and N receive antennas scales only logarithmically with N , as $N \rightarrow \infty$. For a system using N transmit and 1 receive antennas, asymptotically there is no additional capacity to be gained, assuming that the transmit power is divided equally among the N antennas.

Foschini and Gans [1] have shown that the asymptotic capacity of multiple-input, multiple-output (MIMO) Rayleigh fading channels grows, instead, linearly with N when N antennas are used at *both* the transmitter *and* the receiver. Furthermore, in [7], Foschini suggested a layered space–time architecture concept that can attain a tight lower bound on the capacity achievable. In this layered space–time architecture, N information bit streams are transmitted simultaneously (in the same frequency band) using N diversity antennas. The receiver uses another N diversity antennas to decouple and detect the N transmitted signals, one signal at a time. The decoupling process in each of the N processing “layers” involves a combination of *nulling out* the interference from yet undetected signals (N diversity antennas can null up to $N - 1$ interferers, regardless of the angles-of-arrival [5]) and *canceling out* the interference from already detected signals. One very significant aspect of this architecture is that it allows an N -dimensional signal processing problem—which would otherwise be solvable only through multiuser detection methods [8] with m^N complexity (m is the signal constellation size)—to be solved with only N similar 1-D processing steps. Namely, the processing complexity grows only linearly with the promised capacity.

This paper includes two important contributions. First, we show that Foschini’s lower bound is, in fact, the Shannon bound when the output SNR of the space–time processing in each layer is represented by the corresponding “matched filter” bound [6], i.e., the maximum SNR achievable in a hypothetical situation where the array processing weights to suppress the remaining interference in each layer are chosen to maximize the output signal-to-interference-plus-noise ratio and any possible

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intersymbol interference (ISI) is assumed to be completely eliminated by some means of equalization. The “matched filter” bound has been shown to be approachable using minimum mean-square error (MMSE) space–time filtering techniques [6].¹ By showing the equivalence of the generalized Foschini’s bound and the Shannon bound, we essentially prove the optimality of the layered space–time concept.

Second, we present an embodiment of Foschini’s layered space–time concept for a coded system operating at a low average SNR and in the presence of unavoidable ISI. Previously, a different embodiment has been provided in [9] for an uncoded system with variable signal constellation sizes, operating at a high average SNR without ISI. Adding coding redundancy might, at first, seem conflicting with the desire to increase the channel bit rate. Our justification is as follows: First, we seek to enhance the channel capacity from a system perspective. We use “noise” in SNR to represent all system impairments, including thermal noise and multiuser interference. The ability to operate at low SNR’s means that more users per unit area can occupy the same bandwidth simultaneously. Second, we anticipate the use of adaptive-rate coding schemes to permit different degrees of error protection according to the channel SNR’s. Incremental redundancy transmission [10], currently being considered for the Enhance Data Services for GSM Evolution (EDGE; GSM stands for Global System for Mobile Communications) standard, is an efficient way to implement adaptive code rates without requiring channel SNR monitoring. With such adaptive-rate coding, the system does not “waste” spectral resources under good channel conditions.

Meanwhile, the iterative processing principle used in turbo and serial concatenated coding [11]–[15] has been successfully applied to a wide variety of joint detection and decoding problems. One such application is the so-called “turbo equalization” [16]–[19], where successive maximum *a posteriori* (MAP) processing is performed by the equalizer and channel decoder to provide *a priori* information about the transmit sequence to one another. Similar to the layered space–time concept, turbo processing allows a multi-dimensional (*two*-dimensional in this case) problem to be optimally solved with successive 1-D processing steps without much performance penalty. In this paper, we apply the turbo principle to layered space–time processing in order to prevent decision errors produced in each layer from catastrophically affecting the signal detection in subsequent layers.

We consider two possible coded layered space–time structures: one applying coding across the multiple signal processing layers, and the other assuming independent coding within each layer. Similar to [1], we assume a *quasi-static* random Rayleigh channel model, where the channel characteristics are stationary within each data block, but statistically independent between different data blocks, different antennas, and, in the case of dispersive multipath channels, different paths. The system is assumed to have similar ISI situations as in EDGE and GSM, where multipath dispersions may last up to several symbol periods [20]. We show that near-capacity performance is achiev-

able using 1-D processing and coding techniques that are already practical and “legacy-compatible” with the EDGE standard, e.g., the use of bit-interleaved 8-ary phase-shift keying (8-PSK) with rate-1/3 convolutional coding and an equalizer with a similar length and structure.

A slightly different layered space–time approach based on *space–time coding* [23], [24] has been studied in [25]. Although it is difficult to make a general comparison, we will see later that our coded layered space–time approach does by far outperform the results reported in [25] for $N = 4$ and $N = 8$. On the other hand, for $N = 2$, space–time coded quaternary phase-shift keying (QPSK) without layered processing appears to be the best known technique for achieving a spectral efficiency of 2 bps/Hz.

This paper is organized as follows. Section II provides a brief review of Foschini’s layered space–time concept. Section III describes the two coded layered space–time architectures and presents a capacity analysis which reveals the equivalence of a generalized Foschini’s lower bound formula and the true capacity bound. Section IV provides details on the array processing, equalization, and iterative MAP techniques. Section V presents performance results. A summary and conclusions are given in Section VI.

II. BACKGROUND THEORY

We briefly review the theory behind Foschini’s layered space–time concept. The generalized Shannon capacity for a MIMO Rayleigh fading system with N transmit and M receive antennas is given in [1] as

$$C = \log_2 \left[\det \left(\mathbf{I} + \frac{\rho}{N} \mathbf{H} \mathbf{H}^\dagger \right) \right] \quad (1)$$

where \mathbf{H} is an $M \times N$ matrix, the (i, j) th element of which is the normalized channel transfer function of the transmission link between the j th transmit antenna and the i th receive antenna, \mathbf{I} is the $M \times M$ identity matrix, ρ is the average SNR per receive antenna, and $\det(\cdot)$ and superscript \dagger denote determinant and conjugate transpose. It is assumed that the transmit power is equally divided among the N transmit antennas. The normalization of the channel transfer function is done such that the average (over Rayleigh fading) of its squared magnitude is equal to unity.

The lower bound on capacity is provided in [1] as

$$C > \sum_{k=N-M+1}^N \log_2 \left[1 + \frac{\rho}{N} \chi_{2k}^2 \right] \triangleq C_F \quad (2)$$

where χ_{2k}^2 is a chi-squared random variable with $2k$ degrees of freedom. For $M = N$

$$C_F = \sum_{k=1}^N \log_2 \left[1 + \frac{\rho}{N} \chi_{2k}^2 \right]. \quad (3)$$

Since χ_{2k}^2 represents a fading channel with a diversity order of k , the lower-bound capacity in (3) can be viewed as the sum of the capacities of N independent channels with increasing diversity orders from 1 to N . This suggests a layered space–time approach [7] for detecting the N transmitted signals as follows:

¹In a flat fading case, MMSE array processing achieves exactly the “matched filter” bound performance.

