Guest Editorial
Twisted Pair Transmission—Ever Increasing Performances on Ancient Telephone Wires

DIGITAL SUBSCRIBER LINE (DSL) technology for high-speed data transmission over the local-loop telephone twisted pairs was advanced in the labs of several research institutions during the late 1980s and early 1990s. Researchers began to develop and experiment with new transmission ideas and to realize high-speed modems in prototype form. As technology matured and standards evolved, these modems came to be known collectively as "xDSL" modems. The ISDN basic-rate interface, which was developed during the early 1980s and operated at a "mere" 160 kb/s, today is often cited as being the archetype of this technology.

At the time of early research on DSL technology, telephone companies generally shared the belief that copper transmission was doomed to become obsolete very soon because of the rapid deployment of fiber-optic cables. They regarded DSL as an "interim" solution for network access. The reality of fiber-optic deployment, however, did not keep up with predictions mainly for economic reasons. Also, the unforeseen explosion of the Internet made high-speed data transmission over the local loop an immediate necessity.

Today, although fiber-optic transmission is beginning to gain impetus, services employing this technology are by and large only available in some specific areas. Direct fiber-optic connections to subscribers are found mostly inside cities and to big business customers. Network access for small office/home office (SOHO) and residential customers is still mostly copper-based. (One of the exceptions may be Sweden, where a fairly large number of apartment buildings have been provided with 10 Mb/s Ethernet access.) In fact, we are currently witnessing a dramatic increase in the number of xDSL connections worldwide, especially in the form of asymmetric DSL (ADSL). A parallel growth is seen in cable-modem deployment, where the coaxial cable infrastructure, originally intended for the delivery of TV programs, has been upgraded to support interactive two-way communication.

The first J-SAC issue on copper access technologies in August 1991 already referred to HDSL (High-rate DSL) and ADSL, whereas the second issue of December 1995 featured papers on even higher speed techniques, such as 125 Mb/s for LAN applications. Meanwhile a manifold of xDSL technologies have been specified by standards bodies, mainly ETSI TM6, ANSI T1E1.4, and ITU-T. These technologies are summarized in Table I.

As is apparent from this table, the modulation methods adopted across different xDSL technologies are not uniform.

TABLE I

xDSL type	Modulation	Data rates	Bandwidth	No. of pairs
HDSL	2B1Q (4-PAM)	1544 kb/s (North America) 2320 kb/s (Europe) 2 x 1168 kb/s (Europe) 3 x 784 kb/s (Europe)	193 kHz 580 kHz 292 kHz 196 kHz	2 1 2 3
SDSL	16-PAM	≤ 2312 kb/s	< 386 kHz	1
ADSL	DMT with < 256 tones	≤ 6144 (8192) kb/s DS ≤ 786 (640) kb/s US	1104 MHz	1
ADSL lite	DMT with < 128 tones	≤ 1536 kb/s DS ≤ 512 kb/s US	552 kHz	1
VDSL	QAM/CAP or DMT with < 4096 tones	North America: ≤ 13 Mb/s (symm.) ≤ 22/3 Mb/s (asymm.) Europe: ≤ 28.288 Mb/s, more realistic: ≤ 14.464 Mb/s (symm.) ≤ 23.168/4.096 Mb/s (asymm.)	12 MHz	1

Baseband pulse-amplitude modulation (PAM), quadrature-amplitude modulation (QAM) and its close relative known as carrierless amplitude-phase (CAP) modulation, as well as discrete multitone (DMT) modulation, which is baseband orthogonal frequency division multiplex (OFDM), are all employed. To those who have followed the work of the various standards organizations, the contention between proponents of single-carrier and multicarrier modulation is well known.

Baseband and QAM/CAP transmissions both have quite a long and successful history. Both are used in xDSL products. For example, symmetric single-pair DSL (SDSL) uses baseband transmission, and a variant of very high-speed DSL (VDSL) uses QAM/CAP transmission.

Because the widescale commercial applications of multicarrier modulation are more recent than those of its single-carrier counterpart, research in the multicarrier domain is more active. It is, therefore, no coincidence that the majority of the papers in this J-SAC issue focuses on multicarrier transmission.

The issue naturally begins with articles addressing the modeling of basic electromagnetic phenomena and cable properties. The first paper by R. Stolle, titled, "Electromagnetic coupling of twisted pair cables," provides a field-theoretic treatment of coupling mechanisms between transmissions on different wire pairs. Near-end crosstalk (NEXT) and far-end crosstalk (FEXT) modeling for the North American loop plant is the topic of C. Valenti's, "NEXT and FEXT models for twisted-pair North American loop plant." In the article, "Impulse generation with appropriate amplitude, length, inter-arrival, and spectral characteristics," by I. Mann *et al.*, the authors present what we believe is the most recent statistical model of nonstationary impulse noise. In-home cabling often exhibits rather poor transmission characteristics. It is, therefore, important to develop mathemat-

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ical models and to understand transmission performance that can typically be achieved for this type of cabling. This topic is addressed in "Channel modeling and system performance for HomePNA 2.0" by P. Bisaglia *et al.*

As soon as telephone providers started rolling out ADSL services, they realized that knowledge about typical transmission characteristics of their loop plant was insufficient: to determine what services to offer, they would ideally need to be able to characterize each single loop between the central office and each customer. For example, knowledge about cable segmentation and composition as well as noise environment (i.e., the possible crosstalk sources) would be needed. However, the relevant data often are not available or are scattered across different data-bank systems without suitable interfaces. Additionally, even if such systems are in place, data have been found to be too unreliable to be used in connection with planning tools, especially those employed for the installation of high-rate systems that need to operate at their performance limits. Thus, loop qualification from the central-office side has emerged as a topic of major importance for further xDSL deployment. Two papers in this issue, one by S. Galli and D. Waring titled, "Loop makeup identification via single ended testing: beyond mere loop qualification," and the other by T. Bostoen *et al.*, titled, "Estimation of the transfer function of a subscriber loop by means of one-port scattering parameter measurement at the central office," suggest some solutions.

It is well known that interference cancellation techniques can enhance the performance of xDSL systems. Three papers are gathered in this issue under the heading of *Interference Cancellation*. The first two, by C. Zeng *et al.*, titled, "Near-end crosstalk mitigation in ADSL systems," and by G.-H. Im *et al.*, titled, "FEXT cancellation for twisted-pair transmission," address the problem of cancellation in two-pair configurations. In contrast, the third paper, "An approach to analog mitigation of RFI," by P. Ödling *et al.*, concentrates on the mitigation of interference caused by radio signals of various origins. Cancellation techniques are to some extent related to multiuser techniques, which are also addressed here by a series of articles grouped toward the end of the issue. These latter techniques also treat the more general case of multipair configurations.

Under *Channel Equalization* two papers are gathered, one dealing with multicarrier and the other with single-carrier transmission. The paper, "Perfect equalization for DMT systems without guard interval," by S. Trautmann and N. J. Fliege, presents a solution for pure frequency-domain equalization in the case where, to increase transmission efficiency, no guard interval has been provided. J. Yang *et al.* present work on blind equalization that is particularly relevant for downstream VDSL transmission. This paper, titled, "The multimodulus blind equalization and its generalized algorithms," is co-authored by J.J. Werner.

The issue continues with five papers devoted to multicarrier transmission *per se*, three of which deal with modulation and signal-processing aspects and two with synchronization issues. The paper by G. Cherubini *et al.*, "Filtered multitone modulation for very high-speed digital subscriber lines," presents a filter-bank modulation technique that achieves high spectral containment and is well-suited for VDSL transmission. The paper by A. Redfern, titled, "Receiver window design for multicarrier communication systems," discusses a windowing technique that attempts to minimize noise power in the received signal after demodulation. We note that signal windowing is an integral part of the version of DMT that was standardized for VDSL. The critical issue of signal clipping in a DMT system because of a high peak-to-average power ratio is treated in "A new approach for evaluating clipping distortion in multicarrier systems ," by A. R. S. Bahai *et al.*The authors show that modeling clipping distortion as an impulsive-noise-like event rather than as additive Gaussian noise is more realistic, and allows one to account more satisfactorily for the significant bit-error rates observed under signal clipping.

Among the two synchronization papers, N. P. Sands and K. S. Jacobsen present in "Pilotless timing recovery for baseband multicarrier modulation," a method where synchronization is achieved without use of a dedicated pilot tone. In "Autonomous synchronization of a DMT-VDSL system in unbundled networks," R. Nilsson *et al.* discuss a new correlation-based scheme to independently synchronize DMT VDSL modems co-located within the same cable binder. The problem solved is particularly important in connection with the unbundling of the local loop, where modems may be operated by different service providers.

An essential element for a successful operation of VDSL modems is upstream power backoff. The paper by S. Schelstraete, "Defining upstream power backoff for VDSL," describes the general mechanism that has been standardized. The second paper, by B. Wiese and K. S. Jacobsen, shows that one mechanism of power backoff called the "reference noise method" is almost optimum, because the maximum possible loss of data rate due to power backoff is bounded. This paper is titled "Use of the reference noise method bounds the performance loss due to upstream power backoff."

Finally, as mentioned earlier, this issue addresses *multiuser techniques*. The papers under this headline are part of the current trend of cooperative optimization of multipair transmission. We note that the latter can be achieved by installing and operating systems in an "optimized" way, e.g., by using suitable placement, and frequency and power allocations. Alternatively, it is possible to characterize the systems as multi-input multi-output (MIMO) systems and resort to cooperative transmission techniques. These are the options currently seen to further improve performance in exploiting the existing copper infrastructure. With the simple installation rules in place today, telecom operators are still far from the optimum usage of their cable plants.

A MIMO approach for single-sided processing is presented by G. Ginis and J. M. Cioffi in "Vectored transmission for digital subscriber line systems." The proposed solution applies to subscriber loops branching out to customers from a cabinet or central office. Power-allocation issues are treated from a multiuser perspective in "Distributed multiuser power control for digital subscriber lines," by W. Yu *et al.* The third multiuser paper, also the last paper of the issue is titled, "Profile detection in multiuser digital subscriber line systems." In it, A. Salvekar *et al.* present techniques to estimate the characteristics of the "crosstalk channels" that are needed by multiuser transmission methods for DSL systems.

We thank all the reviewers who helped us select and improve the papers for this issue. Many reviewers invested significant time to write detailed comments that were incorporated into the published papers. We trust that their comments were also useful to those authors whose papers could not be accepted. Some reviewers even reviewed more than one paper, and we are especially grateful for their assistance. In total we received 46 papers, of which 21 were accepted. We hope you enjoy the collection.

Before closing this guest editorial, we would like to mention that, with this issue dedicated to twisted-pair transmission, we remember **Dr. Jean-Jacques Werner**, who passed away in 2000. Jean-Jacques, or "JJ," could certainly be considered one of the fathers of xDSL. He was one of few people who always believed in this technology. Following this guest editorial, an "In Memoriam," formulated by our Co-Guest Editor Burt Saltzberg who was JJ's colleague for many years, highlights his achievements.

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Werner Henkel (S'87–M'89) was born in Gelnhausen, Germany, in 1960. He received the Diploma and Dr.-Ing. (Ph.D.) degrees from Darmstadt University of Technology (TUD), Germany, in May 1984, and June 1989, respectively.

From 1989 to 1999, he was with Deutsche Telekom's R&D Labs, Darmstadt, mainly involved in the design of coded modulation schemes for satellite communication and later heading projects for high-rate subscriber-line transmission. Besides the scientific work, support for the German ADSL roll-out was provided. In 1993/1994, he was on sabbatical leave at AT&T Bell Laboratories (now Lucent), Middletown, NJ, Advanced Data Communications Group headed by Dr. J. J. Werner. From 1999, he has been with the newly founded Telecommunications Research Center Vienna, Austria, heading a basic research group dealing with access technologies with a focus on signal processing and coding for xDSL. He has been teaching courses on coding theory at the Universities of Kaiserslautern, Germany, and Vienna, Austria, and industry courses on xDSL. As standardization activities, especially contributions to ETSI TM6 may be mentioned. He was in the organizing committee of ISIT 1997 (publications) and has organized several workshops and courses. Publications are in the areas of coding, coded modulation, frame synchronization, channel modeling, impulse noise, xDSL, single and multicarrier transmission. Current research activities have a focus on multicarrier transmission, MIMO systems, iterative decoding, channel measurement, and modeling.

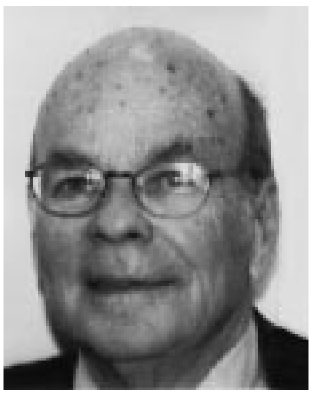
Sedat Ölçer (SM'94) received the Diploma of electrical engineering and the Ph.D. degree from the Swiss Federal Institute of Technology, Lausanne (EPFL), Switzerland, in 1978 and 1982, respectively.

From 1982 to 1984, he was a Research Associate at the Information Systems Laboratory of Stanford University, Stanford, CA, and at Yale University, New Haven, CT. In 1984, he joined the IBM Zurich Research Laboratory, Rüschlikon, Switzerland, where he worked on digital transmission techniques for magnetic recording channels and, more recently, on high-speed data communications for local area networking and network access. His research interests are in digital communications, signal processing and coding, with applications to broadband network access. In 1999, he was Guest Editor for the special issue of *Computer Networks* on Broadband Access Networks, and in 2000, he served as Guest Editor of the *IEEE Communication Magazine* Feature Topic on Very High-Speed Digital Subscriber Lines. He is currently a Technical Editor of the *IEEE Communications Magazine*.

Krista S. Jacobsen received the B.S.E.E. degree from the University of Denver, Denver, CO, in 1991 and the M.S.E.E. and Ph.D. degrees from Stanford University, Stanford, CA, in 1993 and 1996, respectively.

Since 1994, she has worked for Amati Communications Corporation (now Texas Instruments), where she was a member of the team that developed the world's first DMT-based VDSL modem. She is currently responsible for determining and leading execution of Texas Instruments' xDSL standards strategy. She has authored more than 50 standards contributions.

Dr. Jacobsen held a National Science Foundation Graduate Fellowship from 1991–1994, an IEEE Communications Society scholarship in 1993, and an IBM Graduate Fellowship from 1994–1995. She holds two patents.



Burton R. Saltzberg (F'76) received the Sc.D. degree from New York University in 1964. He is a consultant in digital communications with several companies, and presents short courses to international audiences. He was with Bell Laboratories from 1957 through early 1996. His most recent position there, which he held for several years, was technical manager of the Data Theory group. For most of his career, Dr. Saltzberg was engaged in research in communication theory and in analysis and initiation of new data communications offerings over a wide variety of channels. He has published extensively in this field, and was issued 29 U.S. patents. He received the IEEE Communications Society Armstrong Achievement Award in 1991.