Guest Editorial
Wireless Ad Hoc Networks

BECAUSE the subject of this issue is wireless ad hoc networks, it would be beneficial to provide a definition of the phrase ad hoc as it is used in the context of mobile wireless networks. We have as a starting point the common definitions of this phrase, such as "for a specific purpose or occasion" or "for this case alone," and many of us have served on at least one ad hoc committee. But there seems to be a gap between this use of ad hoc and the use of ad hoc in the phrase "wireless ad hoc networks," which suggests that a more descriptive name should be sought.

We have not discovered a universally accepted definition of wireless ad hoc networks, but there are a few features that are shared by most descriptions of such networks that have appeared in the literature. In a wireless ad hoc network, there is no predetermined topology and no central control. Ad hoc networks do not rely on a preexisting fixed infrastructure, such as a wireline backbone network or a base station. The nodes in an ad hoc network communicate without wired connections among themselves by creating a network "on the fly."

The responsibilities for organizing and controlling the network are distributed among the terminals themselves. The entire network is mobile, and the individual terminals are allowed to move at will relative to each other. In an ad hoc network, some pairs of terminals may not be able to communicate directly with each other and relaying of some messages is required, so that they are delivered to their destinations. Such networks are often referred to as multihop or store-and-forward networks. Based on these features, standard cellular networks and wireless fully connected networks do not qualify as ad hoc networks.

Probably the chief difference between ad hoc networks and conventional cellular technology is the apparent lack of a centralized entity within an ad hoc network. There are no base stations or mobile switching centers in an ad hoc network. Consequently, all network protocols must operate in a distributed manner.

The interest in wireless ad hoc networks stems from some of their well-known advantages for certain types of applications. Since there is no fixed infrastructure, a wireless ad hoc network can be deployed quickly. Thus, such networks can be used in situations where either there is no other wireless communication infrastructure present or where such infrastructure cannot be used because of security, cost, or safety reasons, for example. Such a network is tolerant of the failure or departure of terminals, because the network does not rely on a few critical terminals for its organization or control. Similarly, terminals can be added easily to the network. Individuals or vehicles can move throughout the network as needed in order to perform their primary functions without concern for maintaining communications with other entities.

We can summarize the most significant of the previously mentioned features of ad hoc networks by offering the phrase "mobile distributed multihop wireless network" as an alternative to wireless ad hoc network.

Although applications of ad hoc networks are anticipated in the commercial market, most of the interest until now in this technology has been from the military. However, the establishment of the Internet Engineering Task Force, Mobile Ad Hoc Networks (MANET) Working Group, whose charter is to address IP routing in ad hoc networks, is a clear indication that many in this field envision that this technology has, indeed, commercial applicability as well.

The basic idea behind the ad hoc networking paradigm is not new. In fact, the early 1970's DARPA packet radio networks are a clear precursor to the recently revived interest in this technology. However, the current research on this technology expanded into new areas and covers topics not addressed by previous research. For instance, as the current vision of ad hoc networks includes multimedia services, issues such as quality-of-service (QoS) and network-layer multicasting are of major concern. Another example is the integration with other networks, such as the Internet, and the necessity for compatible design of the ad hoc networking protocol with the current Internet protocols.

Some of the challenges of the current research in this area are: routing protocols, QoS, medium access control (MAC), low power design, mobility management, and security. The purpose of this IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS issue is to present some of these problems and to introduce possible solutions. It is, by no means, an exhaustive representation of all the research in the area of ad hoc networks. Rather, it is a sample. We hope that this issue will become a snapshot of milestones in the continuous progress in this very active field.

The 13 papers in this issue are organized as follows. The paper by Rodoplu and Meng addresses the issue of configuration of the network nodes, subject to minimum power requirements. The paper by Ju and Li proposes a new scheduling algorithm, which does not require recomputation of the old transmission schedule when new nodes join the network. In the next paper, Sobrinho and Krishnakumar discuss the application of the black burst distributed MAC scheme in ad hoc networks to support QoS for real-time traffic. Routing protocols and their performance are the subject of the next set of papers. Iwata *et al.* introduce two novel routing schemes for ad hoc networks and compare those with a number of other routing protocols. Garcia-Luna-Aceves and Madruga introduce the core-assisted mesh protocol for multicast routing. In the paper by Pearlman and Haas, the authors discuss how to determine the optimal

Publisher Item Identifier S 0733-8716(99)07444-2.

size of a zone in the zone routing protocol (ZRP) for ad hoc networks and present performance evaluation figures of this routing protocol. Joa-Ng and Lu introduce the peer-to-peer two-level link state routing scheme, a hierarchical approach to routing that does not require cluster heads. In the next paper, Lin and Liu present a routing protocol that supports QoS through end-to-end bandwidth calculation and bandwidth reservation. Maltz *et al.* provide in their paper an analysis of the effect of on-demand operation of routing protocols in an ad hoc networking environment. The core-extraction distributed ad hoc routing protocol that supports quality of service route computation is introduced in the paper by Sivakumar *et al.* In the next paper, McDonald and Znati present their framework for adaptive clustering that allows dynamic grouping of nodes to use a distributed algorithm. The issue of QoS routing in ad hoc networks is addressed in the paper by Chen and Nahrstedt. Their approach is based on a scheme that selects a network path subject to some delay or bandwidth requirements. Finally, a network management protocol for ad hoc networks based on hierarchical clustering is discussed in the paper by Chen *et al.*

ACKNOWLEDGMENT

The Guest Editors thank the authors of all the submitted papers, many of which could not be accommodated in this issue, and they greatly appreciate the time and effort contributed by the reviewers. Special thanks go to S. McDonald and J. F. Hayes for their support and assistance in the preparation of this issue.

ZYGMUNT J. HAAS, *Guest Editor*
Cornell University
Ithaca, NY 14853-3801 USA

MARIO GERLA, *Guest Editor*
University of California
Los Angeles, CA 90024 USA

DAVID B. JOHNSON, *Guest Editor*
Carnegie Mellon University
Pittsburgh, PA 15213-3891 USA

CHARLES E. PERKINS, *Guest Editor*
Sun Microsystems Laboratories
Palo Alto, CA 94303-4900 USA

MICHAEL B. PURSLEY, *Guest Editor*
Clemson University,
Clemson, SC 29634-0915 USA

MARTHA STEENSTRUP, *Guest Editor*
BBN Technologies
Cambridge, MA 02138-1119 USA

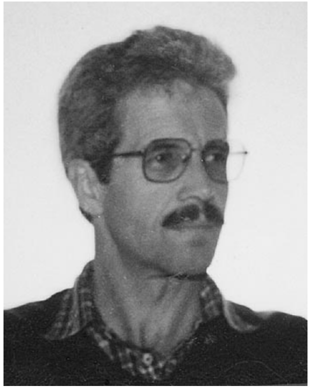
C.-K. TOH, *Guest Editor*
Georgia Institute of Technology,
Atlanta, GA 30332 USA

J. F. HAYES, *J-SAC Board Representative*

Zygmunt J. Haas (S'84–M'88–SM'90) received the B.Sc. degree in electrical engineering in 1979, the M.Sc. degree in electrical engineering in 1985, and the Ph.D. degree from Stanford University, Stanford, CA, in 1988.

He joined AT&T, Bell Laboratories in the Network Research Department in 1988. There, he pursued research on wireless communications, mobility management, fast protocols, optical networks, and optical switching. From 1994 to 1995, he worked for the AT&T Wireless Center of Excellence, where he investigated various aspects of wireless and mobile networking, concentrating on TCP/IP networks. As of August 1995, he joined the faculty of the School of Electrical Engineering at Cornell University, Ithaca, NY, where he is now a tenured Associate Professor.

Dr. Haas is the author of numerous technical papers and holds 12 patents in the fields of high-speed networking, wireless networks, and optical switching. He has organized several workshops, delivered tutorials at major IEEE and ACM conferences, and serves as Editor of several journals. He has been a Guest Editor of three IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS issues ("Gigabit Networks," "Mobile Computing Networks," and "Wireless Ad Hoc Networks"). He is a voting member of ACM and a Vice-Chair of the IEEE Technical Committee on Personal Communications. His interests include mobile and wireless communication and networks, personal communication service, and high-speed communication and protocols.



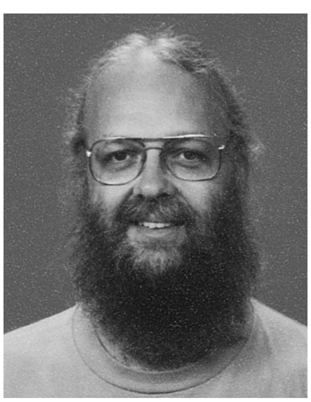
Mario Gerla (M'75) received the graduate degree in electrical engineering from Politecnico di Milano, Italy, in 1966 and the M.S. and Ph.D. degrees in computer science from the University of California, Los Angeles (UCLA), in 1970 and 1973, respectively.

From 1973 to 1976, he was a Manager in Network Analysis Corporation, Glen Cove, NY, where he was involved in several computer network design projects for both government and industry, including performance analysis and topological updating of the ARPANET under a contract from U.S. Department of Defense. From 1976 to 1977, he was with Tran Telecommunication, Los Angeles, CA, where he participated in the development of an integrated packet and circuit network. Since 1977, he has been on the faculty in the Computer Science Department, UCLA. His research interests include the design, performance evaluation, and control of distributed computer communication systems and networks. His current research projects cover the following areas: design and performance evaluation of protocols and control schemes for ad hoc wireless networks; routing, congestion control and bandwidth allocation in wide area networks; and traffic measurements and characterization.

David B. Johnson (S'74–M'77) received the B.A. degree in computer science and mathematical sciences in 1982, the M.S. degree in computer science in 1985, and the Ph.D. degree in computer science in 1990, all from Rice University, Houston, TX.

He is currently an Associate Professor in the School of Computer Science, Carnegie Mellon University, Pittsburgh, PA. His research interests include network protocols, distributed systems, and operating systems. He is leading the Monarch Project at Carnegie Mellon University, developing adaptive networking protocols and architectures to allow truly seamless wireless and mobile networking. Related to this research, he has been active in the Internet Engineering Task Force (IETF) for many years, where he was one on the designers of the Mobile IPv4 protocol and is the primary designer of MobileIPv6. He is an Area Editor for *Mobile Networks and Applications* and for *Mobile Computing and Communications Review* and has been a Guest Editor for issues of several journals.

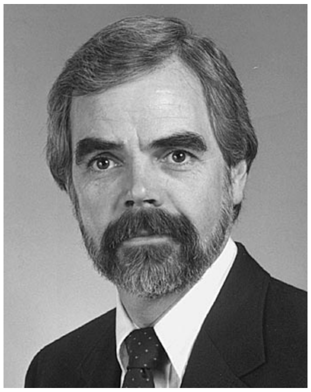
Dr. Johnson was Program Chiar for MobiCom'97 and Technical Vice Chair for Mobile Systems for ICDCS'99, and he has served as a member of the Technical Program Committee for over 15 international conferences and workshops. He is an Executive Committee Member and the Treasurer for ACM SIGMOBILE and is a member of the ACM, IEEE Computer Society, the IEEE Communications Society, USENIX, Sigma Xi, and the Internet Society.



Charles E. Perkins (M'85) received the B.A. degree in mathematics and the M.E.E. degree from Rice University, Houston, TX, and the M.A. degree in mathematics from Columbia University, New York.

He is a Senior Staff Engineer at Sun Laboratories, Palo Alto, CA, investigating mobile wireless networking and dynamic configuration protocols. He is serving as Document Editor for the mobile-IP working group of the Internet Engineering Task Force (IETF) and is the author or coauthor of standard-track documents in the mobileip, svrloc, dynamic host configuration (dhc), and IPng working groups. He is an Associate Editor for *Mobile Communications and Computing Review*, the official publication of ACM SIGMOBILE. He has served on the Internet Architecture Board (IAB) of the IETF. He has authored a book on mobile IP and has published a number of papers and award-winning articles in the areas of mobile networking, resource discovery, and automatic configuration for mobile computers.

Mr. Perkins has served on various committees for the National Research Council and is currently the Chairperson of the Nomadicity Working Team of the Cross Industry Working Team (XIWT). He is the Editor for several ACM and IEEE journals for areas related to wireless networking. He is a member of ISOC, ACM, and the IETF and is on the editorial staff for IEEE INTERNET COMPUTING MAGAZINE.



Michael B. Pursley (S'68–M'68–F'82) received the B.S. degree (with highest distinction) and the M.S. degree in electrical engineering from Purdue University, West Lafayette, IN, in 1967 and 1968, respectively. He received the Ph.D. degree in electrical engineering from the University of Southern California, Los Angeles, in 1974.

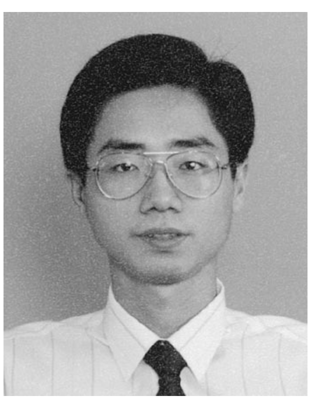
He has several years industrial experience, primarily with the Space and Communications Group of the Hughes Aircraft Company. He was a Hughes Doctoral Fellow and a Research Assistant in the Department of Electrical Engineering at the University of Southern California. From January to June 1974, he was an Acting Assistant Professor in the System Science Department of the University of California, Los Angeles. From June 1974 to July 1993, he was with the Department of Electrical and Computer Engineering and the Coordinated Science Laboratory at the University of Illinois, Urbana, where he was promoted to the rank of Professor in 1980. He is currently the Holcombe Professor of electrical and computer engineering at Clemson University, Clemson, SC. His research is in the general area of communications and information theory with emphasis on spread-spectrum communications, communication over fading channels, applications of error-control coding, protocols for packet radio networks, and mobile communications systems and networks.

Dr. Pursley is a member of Phi Eta Sigma, Tau Beta Pi, and the Institute of Mathematical Statistics. He was elected to three-year terms on the Board of Governors of the IEEE Information Theory Society in 1977 and again in 1989. In 1982, he served as President of the Information Theory Society. He was a Member of the Editorial Board of the PROCEEDINGS OF THE IEEE during 1984–1991 and a Member of the Conference Board for the IEEE Military Communications Conference during 1992–1997. He is currently a member of the Editorial Advisory Board for the *International Journal of Wireless Information Networks* and a Senior Editor for the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS. He served as Technical Program Chairman for the 1979 IEEE International Symposium on Information Theory, Grignano, Italy, and as Cochairman for the 1995 IEEE International Symposium on Information Theory, Whistler, Canada. He was awarded an IEEE Centennial Medal in 1984, and he received the Ellersick Award of the IEEE Communications Society in 1996.

Martha Steenstrup (M'83–SM'98) received the A.B. degree in mathematics and music from Smith College, Northhampton, MA, the M.A. in mathematics from Columbia University, NY, and the Ph.D. degree in computer and information science from the University of Massachusetts, Amherst.

She is a Principal Scientist at BBN Technologies, Cambridge, MA, where her research activities have included self-organization, routing, flow control, and service provision in wireline and wireless networks. She is the Editor of *Routing in Communications Networks* (Englewood Cliffs, NJ: Prentice-Hall, 1995), past Editor of the ACM SIGCOMM quarterly *Commuter Communications Review*, and Guest Editor (with R. Ramanathan) of a 1996 issue of ACM/Baltzer *Mobile Networks and Applications* on routing in mobile wireless networks.

Dr. Steenstrup is a voting member of ACM.



C.-K. Toh (M'92) was born in Singapore in 1965 and was educated in the EEE Department at the University of Manchester Institute of Science and Technology, England, and in electrical engineering and computer science at the Computer Laboratory, University of Cambridge, England. His Ph.D. dissertation was focused on "Protocol Aspects of Mobile Radio Networks."

He founded and then chaired the Cambridge Mobile Radio Special Interest Group from 1994 to 1996. He was with Hughes Aircraft Company, leading research work on ad hoc, satellite, and wireless ATM networks. He was a Project Technical Leader for the DARPA–TTO Deployable and Adaptive Ad Hoc Mobile Wireless Networks (DAMAN) program. As of 1998, he has been with the Georgia Institute of Technology, Atlanta, as an Assistant Professor of electrical and computer engineering, directing the mobile multimedia and high-speed networking laboratory. He works on several aspects of mobile networks (routing, protocols, algorithms, mobility management, etc.). Prior to 1994, he was a Network Specialist, R&D Engineer, and a Technical Staff Member, working on multimedia communications over broadband ISDN. He authored the book *Wireless ATM and Ad Hoc Networks* (Norwell, MA: Kluwer 1996). He has been a Feature Editor for *ACM Mobile Computing and Communications Review*. He serves as an Editorial Board Member of the *Springer-Verlag Personal Technologies Journal*.

Dr. Toh was an Area Editor on wireless networking for the IEEE COMMUNICATIONS SURVEY JOURNAL from 1996 to 1998 and serves as an Editorial Board Member for IEEE INTERNET COMPUTING MAGAZINE. At Cambridge University, he was an Honorary Cambridge Research Scholar. He is a member of the Institute of Electrical Engineers, ACM, USENIX, and a Senior Member of King's College Cambridge Philosophical Society.