
MOBILE COMPUTING

**THE KLUWER INTERNATIONAL SERIES
IN ENGINEERING AND COMPUTER SCIENCE**

MOBILE COMPUTING

edited by

Tomasz Imielinski
Rutgers University

Henry F. Korth
AT&T Bell Laboratories



KLUWER ACADEMIC PUBLISHERS
Boston / Dordrecht / London

Distributors for North America:

Kluwer Academic Publishers
101 Philip Drive
Assinippi Park
Norwell, Massachusetts 02061 USA

Distributors for all other countries:

Kluwer Academic Publishers Group
Distribution Centre
Post Office Box 322
3300 AH Dordrecht, THE NETHERLANDS

Library of Congress Cataloging-in-Publication Data

A C.I.P. Catalogue record for this book is available
from the Library of Congress.

Copyright © 1996 by Kluwer Academic Publishers

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, mechanical, photo-copying, recording, or otherwise, without the prior written permission of the publisher, Kluwer Academic Publishers, 101 Philip Drive, Assinippi Park, Norwell, Massachusetts 02061

Printed on acid-free paper.

Printed in the United States of America

CONTENTS

PREFACE

xxi

1 INTRODUCTION TO MOBILE COMPUTING

Tomasz Imielinski and Henry F. Korth

1

1 Introduction

1

2 Technology Overview

3

3 Research Issues

17

4 Book Content

33

REFERENCES

39

2 THE PARCTAB UBIQUITOUS COMPUTING EXPERIMENT

Roy Want, Bill N. Schilit, Norman I. Adams, Rich Gold, Karin Petersen, David Goldberg, John R. Ellis, and Mark Weiser

45

1 Introduction

45

2 Ubiquitous Computing

47

3 PARCTAB System Design

50

4 User-Interface Design for Palm-Sized Computers

57

5 PARCTAB System Architecture

63

6 Developing System and Application Components

71

7 A Classification of PARCTAB Applications

75

8 Experiences with the PARCTAB System

81

9 Conclusion

91

REFERENCES

97

3 SCALABLE SUPPORT FOR TRANSPARENT MOBILE INTERNETWORKING

<i>David B. Johnson</i>	103
1 Introduction	103
2 Problem Analysis	105
3 The Basic Mobile IP Protocol	108
4 Route Optimization	115
5 Protocol Scalability	121
6 Conclusion	124
REFERENCES	125

4 LOCATION MANAGEMENT FOR NETWORKS WITH MOBILE USERS

<i>B. R. Badrinath and Tomasz Imielinski</i>	129
1 Introduction	129
2 Location Management in the Internet	133
3 Location Management in Cellular Telephone Networks and in PCN	141
4 Performance Issues	145
5 Future: Adaptive Location management	147
6 Conclusions	150
REFERENCES	150

5 DYNAMIC SOURCE ROUTING IN AD HOC WIRELESS NETWORKS

<i>David B. Johnson and David A. Maltz</i>	153
1 Introduction	153
2 Assumptions	157
3 Basic Operation	157
4 Optimizations	162
5 Performance Evaluation	169
6 Related Work	174
7 Conclusion	178
REFERENCES	179

6 ROUTING OVER MULTI-HOP WIRELESS NETWORK OF MOBILE COMPUTERS

<i>Charles E. Perkins and Pravin Bhagwat</i>	183
1 Introduction	184
2 Overview of Routing Methods	185
3 Destination-Sequenced Distance Vector (DSDV) Protocol	187
4 Examples of DSDV in Operation	193
5 Properties of the DSDV Protocol	199
6 Comparison with Other Methods	200
7 Future Work	202
8 Summary	203
REFERENCES	205

7 IMPROVING THE PERFORMANCE OF RELIABLE TRANSPORT PROTOCOLS IN MOBILE COMPUTING ENVIRONMENTS

<i>Ramón Cáceres and Liviu Iftode</i>	207
1 Introduction	208
2 Wireless Networking Testbed	209
3 The Effects of Motion	212
4 Improving Performance	218
5 Wireless Transmission Errors	225
6 Conclusions	227
REFERENCES	228

8 INDIRECT TRANSPORT LAYER PROTOCOLS FOR MOBILE WIRELESS ENVIRONMENT

<i>Ajay V. Bakre and B.R. Badrinath</i>	229
1 Introduction	229
2 System Model	230
3 Indirect Transport Layer	233
4 Implementation and Handoffs	238
5 Performance Results	240
6 Alternatives to Indirect Protocols	247
7 Conclusion and Future Work	249

REFERENCES	251
9 CONNECTING MOBILE WORKSTATIONS TO THE INTERNET OVER A DIGITAL CELLULAR TELEPHONE NETWORK	
<i>Markku Kojo, Kimmo Raatikainen and Timo Alanko</i>	253
1 Introduction	253
2 Mobile Nodes and TCP/IP Protocols	256
3 The Mowgli Communication Architecture	259
4 Enhanced Functionality for Mobility	265
5 Discussion	268
REFERENCES	269
10 ASYNCHRONOUS VIDEO: COORDINATED VIDEO CODING AND TRANSPORT FOR HETEROGENEOUS NETWORKS WITH WIRELESS ACCESS	
<i>Johnathan M. Reason, Louis C. Yun, Allen Y. Lao, and David G. Messerschmitt</i>	271
1 Introduction	272
2 MPEG and Mobile Channels	273
3 System Level Considerations	276
4 QOS and Traffic Capacity	281
5 Video Coding for a Substream Transport	286
6 Results	293
7 Conclusions and Future Work	296
REFERENCES	297
11 WIRELESS PUBLISHING: ISSUES AND SOLUTIONS	
<i>T. Imielinski and S. Viswanathan</i>	299
1 Introduction	299
2 Publishing Mode	301
3 Publishing Using Temporal Addresses	308
4 Publishing Using Multicast Addresses	318
5 Adaptive Publishing	321

6	Other Information Delivery Methods	325
7	Conclusions and Implementation Status	327
	REFERENCES	328
12	BROADCAST DISKS: DATA MANAGEMENT FOR ASYMMETRIC COMMUNICATION ENVIRONMENTS	
	<i>S. Acharya, R. Alonso, M. Franklin, and S. Zdonik</i>	331
1	Introduction	332
2	Structuring the Broadcast Disk	335
3	Client Cache Management	341
4	Modeling the Broadcast Environment	343
5	Experiments and Results	346
6	Previous Work	356
7	Summary and Future Work	358
	REFERENCES	360
13	APPLICATION DESIGN FOR WIRELESS COMPUTING	
	<i>Terri Watson</i>	363
1	Introduction	363
2	Application Design for a Wireless Environment	365
3	Wireless Platform	366
4	W* : A Wireless Application	367
5	Experiences	369
6	Conclusions	371
	REFERENCES	371
14	MOBISAIC: AN INFORMATION SYSTEM FOR A MOBILE WIRELESS COMPUTING ENVIRONMENT	
	<i>Geoffrey M. Voelker and Brian N. Bershad</i>	375
1	Introduction	375
2	System Overview	378
3	Using Dynamic URLs	380
4	Active Documents	382

5	Mobisaic on the Desktop	386
6	Implementation	386
7	Future Work	389
8	Conclusions	393
	REFERENCES	394
15	PROVIDING LOCATION INFORMATION IN A UBIQUITOUS COMPUTING ENVIRONMENT	
	<i>Mike Spreitzer and Marvin Theimer</i>	397
1	Introduction	398
2	Architecture	400
3	Design Considerations	407
4	Status and Experience	413
5	Conclusions	419
	REFERENCES	423
16	UNIX FOR NOMADS: MAKING UNIX SUPPORT MOBILE COMPUTING	
	<i>Michael Bender, Alexander Davidson, Clark Dong, Steven Drach, Anthony Glenning, Karl Jacob, Jack Jia, James Kempf, Nachiappan Periakaruppan, Gale Snow, and Becky Wong</i>	425
1	Introduction	426
2	The Power Management Framework	427
3	System State Checkpoint and Resume	432
4	PCMCIA on Unix	435
5	Serial Wide-Area Connectivity and Link Management	440
6	Nomadic Electronic Mail	443
7	Summary	446
	REFERENCES	447
17	SCHEDULING FOR REDUCED CPU ENERGY	
	<i>Mark Weiser, Brent Welch, Alan Demers, and Scott Shenker</i>	449
1	Introduction	450
2	An Energy Metric for CPUs	450

3	Approach of This Paper	452
4	Trace Data	452
5	Assumptions of the Simulations	453
6	Scheduling Algorithms	455
7	Evaluating the Algorithms	457
8	Discussion and Future Work	462
9	Conclusions	467
	REFERENCES	469
	APPENDIX A	469
A.1	Description of Trace Data	470

18 STORAGE ALTERNATIVES FOR MOBILE COMPUTERS

	<i>Fred Douglass, Ramón Cáceres, M. Frans Kaashoek, P. Krishnan, Kai Li, Brian Marsh, Joshua Tauber</i>	473
1	Introduction	474
2	Architectural Alternatives	476
3	Hardware Measurements	477
4	Trace-Driven Simulation	480
5	Results	486
6	Related Work	498
7	Conclusions	500
8	Differences from the Preceding Version	503

19 DISCONNECTED OPERATION IN THE CODA FILE SYSTEM

	<i>James J. Kistler and M. Satyanarayanan</i>	507
1	Introduction	507
2	Design Overview	508
3	Design Rationale	511
4	Detailed Design and Implementation	515
5	Status and Evaluation	525
6	Related Work	530
7	Future Work	531
8	Conclusions	532
	REFERENCES	533

20 EXPERIENCE WITH DISCONNECTED OPERATION IN A MOBILE COMPUTING ENVIRONMENT

M. Satyanarayanan, James J. Kistler, Lily B. Mummert, Maria R. Ebling, Puneet Kumar, and Qi Lu

	537
1 Introduction	537
2 Constraints of Mobile Computing	538
3 Overview of Coda File System	539
4 Implementation Status	541
5 Qualitative Evaluation	542
6 Quantitative Evaluation	554
7 Work in Progress	563
8 Conclusions	568
REFERENCES	569

21 MOBILITY SUPPORT FOR SALES AND INVENTORY APPLICATIONS

Narayanan Krishnakumar and Ravi Jain

	571
1 Introduction	572
2 Application Scenario: Mobile Sales and Inventory	573
3 System Architecture	574
4 Database System Design	577
5 Mobile Sales Transactions	583
6 Maintaining Service Profiles	588
7 Conclusions	592
REFERENCES	592

22 STRATEGIES FOR QUERY PROCESSING IN MOBILE COMPUTING

Masahiko Tsukamoto, Rieko Kadobayashi and Shojiro Nishio

	595
1 Introduction	595
2 Techniques Used in Mobile Communication Protocols	596
3 Query Processing for Location Sensitive Queries	600
4 Evaluation	608
5 Conclusions	617
REFERENCES	618

23 THE CASE FOR WIRELESS OVERLAY NETWORKS

<i>Randy H. Katz and Eric A. Brewer</i>	621
1 Introduction	621
2 Applications Enabled by Wireless Overlays	623
3 Applications Viewpoint	625
4 Gateway-Centric Network Management	628
5 Overlay Network Management	635
6 Applications Support Services	640
7 Related Work	644
8 Summary and Conclusions	648
REFERENCES	648

24 THE DIANA APPROACH TO MOBILE COMPUTING

<i>Arthur M. Keller, Tahir Ahmad, Mike Clary, Owen Densmore, Steve Gadol, Wei Huang, Behfar Razavi, and Robert Pang</i>	651
1 Introduction	651
2 DIANA—The Overall Architecture	656
3 User Interface and Display Independence	660
4 The DIANA Network Architecture	665
5 Application Development Methodology	670
6 Current Implementation	674
7 Future Issues	674
8 Concluding Remarks	677
REFERENCES	677

25 THE CMU MOBILE COMPUTERS AND THEIR APPLICATION FOR MAINTENANCE

<i>Asim Smailagic and Daniel P. Siewiorek</i>	681
1 Introduction	681
2 CMU Mobile Computers and Their Applications	683
3 VuMan as a Maintenance Assistant	684
4 Application Software	688
5 Conclusions	689

6	Figures	691
	REFERENCES	698
26	GENESIS AND ADVANCED TRAVELER INFORMATION SYSTEMS	
	<i>Shashi Shekhar and Duen-Ren Liu</i>	699
1	Introduction	699
2	Genesis System	704
3	Data Management in Genesis	708
4	Performance Issues in Genesis	715
5	Conclusions	720
	REFERENCES	721
	INDEX	725

CONTRIBUTORS

Norman Adams

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Tahir Ahmad

Stanford University
Computer Science Department
Stanford, California 94303

Timo Alanko

Department of Computer Science
University of Helsinki
P.O.Box 26 FIN
00014 University of Helsinki, Finland

Ajay Bakre

Department of Computer Science
Rutgers University
New Brunswick, NJ 08903

B.R.Badrinath

Department of Computer Science
Rutgers University
New Brunswick, NJ 08903

Michael Bender

Sun Microsystems, Inc.
Mountain View, California.

Brian N. Bershad

Department of Computer Science and Engineering
University of Washington
Seattle, WA 98195

Pravin Bhagwat

University of Maryland
College Park, MD

Eric Brewer

Computer Science Division,
Department of Electrical Engineering and
Computer Sciences
University of California
Berkeley, CA 94720-1776

Ramón Cáceres

AT&T Bell Laboratories
101 Crawfords Corner Road
Holmdel NJ 07733

Mike Clary

Sun Microsystem, Inc.
Mountain View, California

Alexander Davidson

Sun Microsystems, Inc.
Mountain View, California

Alan Demers

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Owen Densmore

Sun Microsystems, Inc.
Mountain View, California

Clark Dong

Sun Microsystems, Inc.
Mountain View, California.

Steven Drach

Sun Microsystems, Inc.
Mountain View, California.

Fred Douglass

AT&T Bell Laboratories
600 Mountain Ave., Room 2B-105
Murray Hill, NJ 07974

Steve Gadol

Sun Microsystems,
Mountain View, California

Anthony Glenning

Sun Microsystems, Inc.
Mountain View, California.

Rich Gold

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

David Goldberg

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Maria R. Ebling

Computer Science Department
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213-3891

John R. Ellis

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Wei Huang

Stanford University,
Computer Science Department
Stanford, California 94303

Tomasz Imielinski

Department of Computer Science
Rutgers University
New Brunswick, NJ 08903

Liviu Iftode

Department of Computer Science
Princeton University
Princeton, NJ 08554

Karl Jacob

Sun Microsystems, Inc.
Mountain View, California.

Jack Jia

Sun Microsystems, Inc.
Mountain View, California.

Ravi Jain

Bell Communication Research
445 South Street
Morristown, NJ 07960

David B. Johnson

Computer Science Department
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213-3891

M. Frans Kaashoek

Massachusetts Institute of Technology
Cambridge, MA

Rieko Kadobayashi

ATR Media Integration
Communications Research Laboratories
Seika-cho, Soraku-gun
Kyoto 619-02, Japan

Randy Katz

Computer Science Division
Department of Electrical Engineering and
Computer Sciences
University of California
Berkeley, CA 94720-1776

Arthur M. Keller

Stanford University,
Computer Science Department
Stanford, California 94303

James Kempf

Sun Microsystems, Inc.
Mountain View, California.

J.Kistler

Computer Science Department
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213-3891

Markku Kojo

Department of Computer Science
University of Helsinki
P.O.Box 26 FIN
00014 University of Helsinki, Finland

Hank Korth

AT&T Bell Laboratories
Murray Hill, NJ 07974

Narayanan Krishnakumar

Bell Communication Research
445 South Street
Morristown, NJ 07960

P. Krishnan

AT&T Bell Laboratories,
Holmdel, NJ 07733

Puneet Kumar

Computer Science Department
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213-3891

Allen Y. Lao

Computer Science Division
Department of Electrical Engineering and
Computer Sciences
University of California
Berkeley, CA 94720-1776

Kai Li

Computer Science Department,
Princeton University
Princeton, NJ 08544

Duen-Ren Liu

Institute of Information Management
National Chiao Tung University, Hsinchu
Taiwan, Republic of China

Qi Lu

Computer Science Department
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213-3891

David Maltz

Computer Science Department
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213-3891

Brian Marsh

D.E. Shaw & Co.
New York, NY

David G. Messerschmitt

Computer Science Division
Department of Electrical Engineering and
Computer Sciences
University of California
Berkeley, CA 94720-1776

Lilly B. Mummert

Computer Science Department
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213-3891

Shojiro Nishio

Dept. of Information Systems Engineering,
Faculty of Engineering, Osaka University
2-1 Yamadaoka, Suita, Osaka 565, Japan

Robert Pang

Stanford University
Computer Science Department
Stanford, California 94303

Nachiappan Periakaruppan

Sun Microsystems, Inc.
Mountain View, California.

Charles E. Perkins

IBM Watson Research Center
Yorktown Heights, NY

Karin Petersen

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Kimmo Raatikainen

Department of Computer Science
University of Helsinki
P.O.Box 26 FIN
00014 University of Helsinki, Finland

Behfar Razavi

Sun Microsystems,
Mountain View, California

Johnathan M. Reason

Computer Science Division, Department
of Electrical
Engineering and Computer Sciences, Uni-
versity of California
Berkeley, CA 94720-1776

M. Satyanarayanan

Computer Science Department
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213-3891

Bill N Schlitt

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Shashi Shekhar

Department of Computer Science
University of Minnesota, Twin Cities,
Minneapolis, Minnesota

Scott Shenker

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Daniel P. Siewiorek

Engineering Design Research Center
Carnegie Mellon University
Pittsburgh, PA 15213

Asim Smailagic

Engineering Design Research Center
Carnegie Mellon University
Pittsburgh, PA 15213

Gale Snow

Sun Microsystems, Inc.
Mountain View, California.

Mike Spreitzer

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Joshua Tauber

Massachusetts Institute of Technology
Cambridge, MA

Marvin Theirmer

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Masahiko Tsukamoto

Dept. of Information Systems Engineering,
Faculty of Engineering, Osaka University
2-1 Yamadaoka, Suita, Osaka 565, Japan

Geoffrey M. Voelker

Department of Computer Science and Engineering
University of Washington
Seattle, WA 98195

S. Viswanathan

Bell Communication Research,
445 South Street,
Morristown, NJ 07960

Roy Want

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Terri Watson

Department of Computer Science & Engineering
University of Washington
Seattle, WA 98195

Mark Weiser

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Brent Welch

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, California, 94301

Becky Wong

Sun Microsystems, Inc.
Mountain View, California.

Louis C. Yun

Computer Science Division, Department
of Electrical
Engineering and Computer Sciences, Uni-
versity of California
Berkeley, CA 94720-1776

PREFACE

The rapid development of wireless digital communication technology has created capabilities that software systems are only beginning to exploit. The falling cost of both communication and of mobile computing devices (laptop computers, hand-held computers, etc.) is making wireless computing affordable not only to business users but also to consumers.

Mobile computing is not a “scaled-down” version of the established and well-studied field of distributed computing. The nature of wireless communication media and the mobility of computers combine to create fundamentally new problems in networking, operating systems, and information systems. Furthermore, many of the applications envisioned for mobile computing place novel demands on software systems.

Although mobile computing is still in its infancy, some basic concepts have been identified and several seminal experimental systems developed. This book includes a set of contributed papers that describe these concepts and systems. Other papers describe applications that are currently being deployed and tested. The first chapter offers an introduction to the field of mobile computing, a survey of technical issues, and a summary of the papers that comprise subsequent chapters. We have chosen to reprint several key papers that appeared previously in conference proceedings. Many of the papers in this book are being published here for the first time. Of these new papers, some are expanded versions of papers first presented at the NSF-sponsored Mobidata Workshop on Mobile and Wireless Information Systems, held at Rutgers University on Oct 31 and Nov 1, 1994.

Many people and organizations assisted us in this project. Ron Ashany and Maria Zemankova of NSF helped provide support for the workshop that spawned this project. Bob Holland of Kluwer Academic Publishers has assisted in seeing the effort through to completion. We conducted a formal refereeing process for original papers in this book and would like to thank those referees, though they remain anonymous. S. Viswanathan assisted us extensively with text format-

ting. Above all, we thank the authors who have contributed their papers to this collection.

Hank would like to thank his wife, Joan, and children Abby and Joe for their understanding and patience. Tomasz would like to thank his wife Celina and sons, Marcin and Konrad, for their support and encouragement.