Chad R. Meiners
Alex X. Liu
Eric Torng

Hardware Based Packet Classification for High Speed Internet Routers

Springer

Hardware Based Packet Classification for High Speed Internet Routers

Chad R. Meiners • Alex X. Liu • Eric Torng

Hardware Based Packet Classification for High Speed Internet Routers

Springer

Chad R. Meiners
Michigan State University
Department of Computer Science
and Engineering
Engineering Building 3115
East Lansing, MI 48824-1226
USA
meinersc@cse.msu.edu

Alex X. Liu
Michigan State University
Department of Computer Science
and Engineering
Engineering Building 3115
East Lansing, MI 48824-1226
USA
alexliu@cse.msu.edu

Eric Torng
Michigan State University
Department of Computer Science
and Engineering
Engineering Building 3115
East Lansing, MI 48824-1226
USA
torng@msu.edu

This material is based upon work supported by the National Science Foundation under Grant No. 0916044. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

ISBN 978-1-4419-6699-5 e-ISBN 978-1-4419-6700-8
DOI 10.1007/978-1-4419-6700-8
Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2010928719

© Springer Science+Business Media, LLC 2010
All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.
The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

This book is dedicated to chance encounters at the correct time.
– Chad Meiners

Dedicated with love and respect
to my parents Shuxiang Wang and Yuhai Liu (God rest his soul),
to Huibo Heidi Ma
to my twin sons Max Boyang and Louis Boyang,
to whom I owe all that I am and all that I have accomplished.
– Alex X. Liu

Dedicated to Pat and Annika.
– Eric Torng

Contents

1 **Introduction** 1
  1.1 Motivation 2
  1.2 Contribution 3

2 **Background** 5
  2.1 Firewall decision diagrams 6
  2.2 One-Dimensional Classifier Minimization 9

3 **Related Work** 15
  3.1 TCAM Based Classifiers 15
    3.1.1 Classifier Minimization: 15
    3.1.2 Range Encoding: 18
    3.1.3 Circuit Modification: 20
  3.2 Software Based Techniques 20
    3.2.1 Parallel decomposition 21
    3.2.2 Decision Trees 23

Part I Equivalent Transformation Techniques

4 **TCAM Razor** 31
  4.1 Multi-dimensional TCAM Minimization: The Basics 31
    4.1.1 Conversion to Firewall Decision Diagrams 31
    4.1.2 Multi-dimensional TCAM Minimization 32
    4.1.3 Removing Redundant Rules 34
    4.1.4 The Algorithm 34
    4.1.5 TCAM Update 35
  4.2 Multi-dimensional TCAM Minimization: The Optimization Techniques 35
    4.2.1 Lazy Copying in FDD Construction 35
    4.2.2 Hashing in FDD Reduction 36

5 Bit Weaving ... 41
5.1 Bit Swapping ... 43
5.1.1 Prefix Bit Swapping Algorithm ... 43
5.1.2 Minimal Cross-Free Classifier Partitioning Algorithm ... 45
5.1.3 Partial List Minimization Algorithm ... 47
5.2 Bit Merging ... 47
5.2.1 Definitions ... 48
5.2.2 Bit Merging Algorithm (BMA) ... 48
5.3 Discussion ... 51
5.3.1 Redundancy Removal ... 51
5.3.2 Incremental Classifier Updates ... 51
5.3.3 Composability of Bit Weaving ... 52
5.3.4 Prefix Shadowing ... 53
5.4 Complexity Analysis of Bit Weaving ... 54

6 All-Match Redundancy Removal ... 57
6.1 All-Match Based Redundancy Theorem ... 57
6.1.1 All-Match FDDs ... 57
6.1.2 The All-Match Based Redundancy Theorem ... 59
6.2 All-Match Based Redundancy Removal ... 60
6.2.1 The All-Match FDD Construction Algorithm ... 60
6.2.2 The All-Match Based Redundancy Removal Algorithm ... 60
6.2.3 Proof of Complete Redundancy Removal ... 63
6.3 Optimization Techniques ... 64
6.3.1 Decision Chaining ... 64
6.3.2 Isomorphic Terminal Nodes Elimination ... 66
6.4 Classifier Incremental Updates ... 67
6.4.1 Rule Insertion ... 68
6.4.2 Rule Deletion ... 68
6.4.3 Rule Modification ... 69
6.5 Redundancy Analysis ... 69

Part II New Architectural Approaches

7 Sequential Decomposition ... 75
7.1 Multi-Lookup Approach ... 77
7.1.1 Constructing Multi-lookup Table ... 77
7.1.2 Packet Processing ... 80
7.1.3 Analysis ... 81
7.2 Pipelined-lookup Approach ... 82
7.2.1 Pipelined-Table Construction ... 82
7.2.2 Packet Processing ... 84
7.2.3 Analysis ... 84
7.3 Packing Approach ... 85
7.3.1 Strict Partitioning ... 86

7.3.2 Shadow Packing 89
7.3.3 Strict Partitioning vs. Shadow Packing 93
7.4 Table Consolidation 93
7.4.1 Table Consolidation Algorithm 93
7.4.2 Hierarchical Table Consolidation 94
7.4.3 TCAM/SRAM Space Tradeoff via Bounded Consolidation . 96
7.5 One-Dimensional Table Consolidation 96
7.5.1 Table Consolidation with Sequential Decomposition 96
7.5.2 Coping with More Fields than TCAM chips 97
7.6 Implementation Issues 97
7.6.1 TCAM Update 97
7.6.2 Non-ordered FDDs 98
7.6.3 Lookup Short Circuiting 98
7.6.4 Best Variable Ordering 99

8 Topological Transformations 101
8.1 Topological Transformation 103
8.1.1 Architectures 103
8.1.2 Measuring TCAM space 105
8.1.3 TCAM Update 106
8.2 Domain Compression 106
8.2.1 Step 1: Compute Equivalence Classes 107
8.2.2 Step 2: Construct Transformers 107
8.2.3 Step 3: Construct Transformed Classifier 109
8.3 Prefix Alignment 111
8.3.1 Prefix Alignment Overview 111
8.3.2 One-dimensional Prefix Alignment 113
8.3.3 Multi-Dimensional Prefix Alignment 116
8.3.4 Composing with Domain Compression 117

References 119

Index 123

List of Figures

2.1 Illustration of FDD construction 8
2.2 An example one-dimensional TCAM minimization problem 12
2.3 Illustration of dynamic program 12

4.1 A firewall decision diagram 32
4.2 “Virtual” one-dimensional packet classifier 33
4.3 Lazing copying of subgraphs 36
4.4 Example of lazing copying 37
4.5a Before FDD reduction 37
4.5b After FDD reduction 37

5.1 Example of the bit weaving approach 42
5.2 Example of bit-swapping 45
5.3 Applying bit weaving algorithm to an example classifier 45
5.4 Example of Bit Merging Algorithm Execution 50

6.1 A simple packet classifier 58
6.2 An all-match FDD for the packet classifier in Fig 6.1 58
6.3 Constructing an all-match FDD 61
6.4 The containment list and the residency List for the all-match FDD . . 62
6.5 The resulting packet classifier after removing redundant rules 63
6.6 Constructing an all-match tree with decision chaining 66
6.7 All-Match Tree with decision tree chaining constructed in rule order and reverse order. 67

7.1 Reducing information redundancy 76
7.2 FDD generation and reduction 78
7.3 The Multi-lookup scheme 79
7.4 Table generation and table mergence in the pipelined-lookup approach 83
7.5 Example of a pipelined-lookup 84

7.6 Strict partitioning of a TCAM chip 87
7.7 Decisions in SRAM 87
7.8 Reassigning the table IDs 88
7.9 Shadow packed tables & shadow packing tree 90
7.10 The shadow packing process. 92
7.11 Consolidation of 2-dimensional tables 94
7.12 Table consolidation for pipelined-lookup sequential decomposition . . 95

8.1 Example of topological transformations 102
8.2 Multi-lookup architecture 104
8.3 Parallel pipelined-lookup architecture 104
8.4 Chained pipelined-lookup architecture 105
8.5 Step 1 of domain compression 108
8.6 Step 2 of domain compression 109
8.7 Step 3 of domain compression 109
8.8 Example of 1-D prefix alignment 112

List of Tables

1.1 An example packet classifier 1
1.2 TCAM Razor output for the example packet classifier in Table 1.1 . . 1

4.1 A minimum packet classifier corresponding to v_2 in Fig. 4.1 32
4.2 A minimum packet classifier corresponding to v_3 in Fig. 4.1 33
4.3 A minimum packet classifier corresponding to v_1 in Fig. 4.1 34
4.4 Packet classifier generated from the FDD in Figure 4.1 34
4.5 Rules from the FDDs in Figure 4.5a and Figure 4.5b 38

5.1 The second partition benefits from the prefix shadow of the first partition 53
5.2 The output of bit merging determines the input. 54
5.3 The set of all ternary covers generated per round 55

Chapter 1
Introduction

Packet classification, which is widely used on the Internet, is the core mechanism that enables routers to perform many networking services such as firewall packet filtering, virtual private networks (VPNs), network address translation (NAT), quality of service (QoS), load balancing, traffic accounting and monitoring, differentiated services (Diffserv), etc. As more services are deployed on the Internet, packet classification grows in demand and importance.

The function of a packet classification system is to map each packet to a decision (i.e.,, action) according to a sequence (i.e.,, ordered list) of rules, which is called a packet classifier. Each rule in a packet classifier has a predicate over some packet header fields and a decision to be performed upon the packets that match the predicate. To resolve possible conflicts among rules in a classifier, the decision for each packet is the decision of the first (i.e., highest priority) rule that the packet matches. Table 1.1 shows an example packet classifier of two rules. The format of these rules is based upon the format used in Access Control Lists on Cisco routers.

Rule	Source IP	Destination IP	Source Port	Destination Port	Protocol	Action
r_1	1.2.3.0/24	192.168.0.1	[1,65534]	[1,65534]	TCP	accept
r_2	*	*	*	*	*	discard

Table 1.1 An example packet classifier

Rule	Source IP	Destination IP	Source Port	Destination Port	Protocol	Action
r_1	1.2.3.0/24	192.168.0.1	0	*	*	discard
r_2	1.2.3.0/24	192.168.0.1	65535	*	*	discard
r_3	1.2.3.0/24	192.168.0.1	*	0	*	discard
r_4	1.2.3.0/24	192.168.0.1	*	65535	*	discard
r_5	1.2.3.0/24	192.168.0.1	[0,65535]	[0,65535]	TCP	accept
r_6	*	*	*	*	*	discard

Table 1.2 TCAM Razor output for the example packet classifier in Table 1.1

C. R. Meiners et al., *Hardware Based Packet Classification for High Speed Internet Routers,*
DOI 10.1007/978-1-4419-6700-8_1, © Springer Science+Business Media, LLC 2010