

University of Wollongong - Research Online

Thesis Collection

Title: Content distribution networks over shared infrastructure : a paradigm for future content network deployment

Author: Thanh Vinh Nguyen

Year: 2005

Repository DOI:

Copyright Warning

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site.

You are reminded of the following: This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author. Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material.

Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Research Online is the open access repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

2005

Content distribution networks over shared infrastructure : a paradigm for future content network deployment

Thanh Vinh Nguyen
University of Wollongong

Follow this and additional works at: <https://ro.uow.edu.au/theses>

University of Wollongong

Copyright Warning

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site.

You are reminded of the following: This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author. Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material.

Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Nguyen, Thanh Vinh, Content distribution networks over shared infrastructure : a paradigm for future content network deployment, PhD thesis, School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, 2005. <http://ro.uow.edu.au/theses/411>

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Content Distribution Networks over Shared
Infrastructure
A Paradigm for Future Content Network
Deployment

A thesis submitted in fulfilment of the
requirements for the award of the degree

Doctor of Philosophy

from

THE UNIVERSITY OF WOLLONGONG

by

Thanh Vinh Nguyen
Bachelor of Engineering (Honours Class I)

SCHOOL OF ELECTRICAL, COMPUTER
AND TELECOMMUNICATIONS ENGINEERING
2005

Abstract

In this thesis we propose and explore the Overlay Distribution Network (ODN) concept as an alternative, more cost effective and more flexible deployment approach for Content Distribution Networks (CDN). Currently CDNs are established by deploying a dedicated server infrastructure spanning the Internet, which is prohibitively expensive. With ODN, we propose to lease transport and server resources from server and network providers to establish an overlay network of virtual servers and connecting virtual links, which is then used to deliver content in a similar manner to traditional CDNs. Such deployment strategy is expected to be less costly and could allow content network topologies and capacities to be adjusted on-the-fly according to demand. The aim of this thesis is to address the research issues that arise as a result of this new deployment approach. One of the major issues considered is ODN provisioning, which involves topology planning, resource dimensioning and content replica placement. ODN provisioning is significantly different from and more complex than its traditional CDN counterpart due to the nature of the shared infrastructure environment. ODN provisioning would not only have a different optimization objective but also require topology planning, resource dimensioning and content replica placement problems, which are currently addressed independently, to be addressed jointly.

To address this ODN provisioning challenge, we develop a provisioning framework that could be used to formulate ODN provisioning models that meet these new requirements. ODN provisioning models for a number of key content distribution applications, including web content distribution, pay-per-view content distribution and live streaming multimedia distribution, are then developed and studied. The models are formulated as mixed integer linear programming optimizations that aim to determine the optimal ODN topology, capacity and content replication pattern, which

deliver satisfactory service performance at the minimum cost or maximum profit.

As the above ODN provisioning models belong to the NP (Non-deterministic Polynomial) class of problems, they have extremely high complexity and cannot be solved efficiently for realistically large networks. To tackle this difficulty we develop heuristics that aim to find near optimal solutions with less computation effort. Experimental results show that our proposed heuristics are efficient and able find solutions reasonably close to the optimal (within 36% for the web ODN provisioning problem and 20% for the pay-per-view and live streaming multimedia ODN provisioning problems). Our study also demonstrates that provisioning could become significantly inefficient if the heuristics were not designed properly. For example in the web content ODN provisioning problem, a greedy heuristic adapted from existing CDN replica placement heuristics could produce ODN topologies up to 2.5 times more costly compared to a Lagrangian heuristic designed based the problem formulation structure.

As part of the ODN provisioning study, we also explore the use of content clustering within the ODN provisioning process. By grouping similar content items together into clusters, which are then considered as a single item during provisioning, content clustering would help reduce provisioning complexity and allow the provisioning models to handle problems with significantly larger number of content items. We show that clustering methods previously developed for CDNs do not work well in the ODN environment. Thus we propose a new hierarchical clustering scheme, where content items are clustered based on first delivery resource requirements and then spatial demand distribution. Experimental results demonstrate that this clustering scheme has significant performance improvements over the existing ones.

In this thesis we also look into the future and study the ability of the ODN to support applications that require QoS network paths among servers. To enable better support for such applications, we propose to enhance the ODN architecture with switching capabilities that allow ODN owners to control the flow of traffic within their ODN backbone. We examine and demonstrate the benefits of such capabilities using both quantitative and qualitative studies and then develop a shared switch architecture that could be used to provide such support in a shared infrastructure environment.

Statement of Originality

This is to certify that the work described in this thesis is entirely my own, except where due reference is made in the text.

No work in this thesis has been submitted for a degree to any other university or institution.

Signed

Thành Vinh Nguyễn

22 August, 2005

Acknowledgments

I would like to thank my supervisors, Professor Farzad Safaei and Dr Paul Boustead, for their dedication, their much appreciated guidance, help and encouragement. I would like to thank Professor Joe Chicharo, who has opened the door for me to pursue my dreams. I would also like to thank Dr Chun Tung Chou, whose guidance during the first stage of the PhD was crucial in shaping the course my research.

I am also very grateful towards the Cooperative Research Center for Smart Internet Technologies, who has funded this work.

I would like to thank my family: my parents, brothers and sisters, whose thoughts are always with me, my other half, Pei Juan Chen, whose love and support has made this all possible.

Last but not least, I would like to express sincere appreciation and gratitude to all members of TITR lab for their support and friendship. It has been a very memorable experience.

*Những cộng trừ nhân chia
Đẫn con đi mãi miết . . .*

*plus minus divide and multiply (the study of science)
forever lead you on the journey of knowledge and discovery*

Mom's poem

Contents

1	Introduction	1
1.1	Background	1
1.2	Thesis Objectives	4
1.3	Thesis Outline	7
1.4	Publications	9
2	Literature Review	11
2.1	Introduction	11
2.2	Content Distribution Network Overview	11
2.2.1	Driving Force and Basic Concept	11
2.2.2	CDN Deployment and Operation	14
2.3	Content Distribution Internetworking	16
2.4	CDN Provisioning	18
2.4.1	Provisioning CDN for Web Content	19
2.4.2	Provisioning CDN for Multimedia Content	24
2.5	CDN Content Consistency	26
2.6	CDN Request Routing	28
2.7	Concluding remarks	30
3	An ODN Provisioning Framework	33

3.1	Introduction	33
3.2	ODN Concept	34
3.3	ODN Provisioning versus CDN Provisioning	36
3.4	ODN Provisioning Framework	38
3.5	Conclusion	40
4	Provisioning ODN for Web Content Distribution	41
4.1	Introduction	41
4.2	Provisioning Problem Formulation	43
4.2.1	Input Parameters	43
4.2.2	Decision Variables	44
4.2.3	Optimization Model	45
4.2.4	Problem Complexity	47
4.3	Lagrangian Heuristic	48
4.3.1	Relaxing the Problem	49
4.3.2	Solving Subproblems	50
4.3.3	Constructing a Feasible Solution	52
4.3.4	Subgradient Procedure	52
4.4	Two-Level Greedy Search Heuristic	53
4.4.1	Analysis	53
4.4.2	Heuristic Outline	54
4.5	CDN-based Greedy Search Heuristic	56
4.6	Numerical Results	58
4.6.1	Performance of CDN-based Greedy Heuristic	58
4.6.2	Performance of Lagrangian and Two-Level Greedy Heuristics	60
4.7	Conclusion	63

5	Provisioning ODN for Pay-Per-View Content Distribution	65
5.1	Introduction	65
5.2	Provisioning Problem Formulation	67
5.2.1	Assumptions	67
5.2.2	Input Parameters	67
5.2.3	Decision Variables	69
5.2.4	Formulation	69
5.2.5	Problem Complexity	70
5.3	Alternative Provisioning Models	72
5.4	Heuristic Procedure	76
5.4.1	Applying Lagrangian Relaxation	76
5.4.2	Constructing a Feasible Solution	78
5.4.3	Subgradient Procedure	80
5.5	Heuristic Results	81
5.5.1	Observations	81
5.6	Conclusion	85
6	Provisioning ODN for Live Multimedia Content Distribution	87
6.1	Introduction	87
6.2	Provisioning Problem Formulation	90
6.2.1	Input Parameters	90
6.2.2	Decision Variables	91
6.2.3	Formulation	92
6.2.4	Problem Complexity	95
6.3	Heuristic Procedure	96
6.3.1	Applying Lagrangian Relaxation	96

6.3.2	Solving the Subproblems	99
6.3.3	Constructing a Feasible Solution	101
6.3.4	Subgradient Procedure	103
6.4	Online Optimization	104
6.5	Numerical Results	107
6.5.1	Provisioning Model Behavior	107
6.5.2	Heuristic Performance	108
6.5.3	Online Optimization	112
6.6	Conclusion	115
7	Improving ODN Provisioning Scalability with Content Clustering	118
7.1	Introduction	118
7.2	General Clustering Framework	120
7.3	Content Clustering in ODN Provisioning	123
7.3.1	Analysis	123
7.3.2	Deficiencies in Existing Clustering Metrics	124
7.3.3	Modifying the Clustering Process	129
7.4	Conclusion	132
8	Networking Support in ODN	135
8.1	Introduction	135
8.2	Why Switching Support?	136
8.3	Switching and Bandwidth Efficiency	139
8.3.1	Network, Cost and Bandwidth Demand Models	140
8.3.2	Link Provisioning Models	141
8.3.3	Numerical Results	146

8.3.4	Remarks	150
8.4	Providing Switching Support in a Shared Infrastructure Environment	150
8.4.1	The Challenge	150
8.4.2	The Proposed Solution	151
8.4.3	A Shared Switch Architecture	153
8.5	Conclusion	159
9	Conclusions	161
9.1	Overview	161
9.2	Major Conclusions	163
9.2.1	ODN Provisioning Framework	163
9.2.2	Provisioning ODN for Web Content Distribution	164
9.2.3	Provisioning ODN for Pay-Per-View Content Distribution	165
9.2.4	Provisioning ODN for Live Multimedia Content Distribution	165
9.2.5	Improving ODN Provisioning Scalability with Content Clus- tering	167
9.2.6	Networking Support in ODN	168
9.3	Summary of Major Contributions	169
9.4	Future Work	170
A	Lagrangian Multiplier Update Procedures	182
A.1	Introduction	182
A.2	Adjusting Multipliers in the Web ODN Provisioning Problem	182
A.3	Adjusting Multipliers in the Pay-Per-View ODN Provisioning Problem	183
A.4	Adjusting Multipliers in the Streaming ODN Provisioning Problem	184
A.5	Other Notes	185

B	Solving the Subproblems	187
B.1	Solving subproblems Q_1 (5.10) and Q_2 (5.11)	187
B.2	Solving subproblem S_3 (6.17)	189
C	Estimating Minimum Number of Replicas	193

List of Figures

2.1	Web content caching	12
2.2	Web server clustering	12
2.3	Delivering content with Content Distribution Networks	14
2.4	A DNS request routing example	15
3.1	An Example ODN Topology	34
3.2	ODN Provisioning Framework	39
4.1	Comparing ODN costs by different provisioning heuristics in the presence of different cost variations	59
5.1	Impact of ODN provisioning model selection on pay-per-view content distribution profit	74
5.2	Comparing different content ranking methods for problems with progressively decreasing server capacities	84
5.3	Solution bounds for the first 1000 iterations	85
6.1	Overlay topology changes in reaction to resource cost variations: (a) high bandwidth and low server cost (b) server cost $\times 10$ (c) server cost $\times 20$	108
6.2	Normalized heuristic solutions obtained with different solution construction methods plotted against link cost multipliers, for 60-node graphs with different link density	110

6.3	Normalized heuristic solutions obtained with different solution construction methods plotted against server cost multipliers, in a graph with link probability 0.9	111
6.4	Normalized heuristic solution obtained with <i>simple paths</i> procedure, with normalized number of established proxies super-imposed	111
6.5	Normalized total service utility by different online optimization methods vs. demand variation created by different types of demand fluctuations	116
7.1	Clustering results for different clustering metrics in the ODN provisioning problem for web content with random demand patterns (lower is better)	125
7.2	Clustering results for different clustering metrics in the ODN provisioning problem for web content with global demand patterns (lower is better)	126
7.3	Results for spatial demand clustering in the ODN provisioning problem for pay-per-view content with different resource requirement variations (higher is better)	127
7.4	Results for spatial demand clustering in the ODN provisioning problem for pay-per-view content with different revenue variations (higher is better)	128
7.5	Results for spatial demand clustering in the ODN provisioning problem for live streaming content with different resource requirement variations (lower is better)	129
7.6	Comparing the performance of clustering by original spatial demand distribution and weighted demand distribution in ODN provisioning for pay-per-view content, where revenue is randomly generated between 1 and 50 (higher is better)	130
7.7	Hierarchical clustering in pay-per-view ODN provisioning problem (higher is better)	132
7.8	Hierarchical clustering in live streaming ODN provisioning problem (lower is better)	133
8.1	Example transport options for ODN backbone connectivity	137
8.2	Bandwidth cost with application flow switching	147

8.3	Bandwidth cost with server flow switching	148
8.4	Switched/non-switched bandwidth cost ratio achieved with different Best-effort:QoS traffic volume ratios	149
8.5	Shared switching resource concept	152
8.6	A Shared Label Switch Architecture	153
8.7	Example switching operations	155
8.8	Implementing a shared switch by extending an existing MPLS switch	158

List of Tables

4.1	Parameters and Variables for Web Content ODN Provisioning Model	45
4.2	Numerical Results for Web Content ODN Provisioning	62
5.1	Parameters and Variables for Pay-Per-View ODN Provisioning Model	71
5.2	Numerical Results for Pay-Per-View Content ODN Provisioning . .	82
6.1	Parameters and Variables for Streaming ODN Provisioning Model .	93
6.2	Numerical Results for Streaming Content ODN Provisioning	113

List of Abbreviations

AS	Autonomous System
ATM	Asynchronous Transfer Mode
BGP	Border Gateway Protocol
CDN	Content Distribution Network
CDI	Content Distribution Internetworking
CIG	Content Internetworking Gateway
CPU	Central Processing Unit
DNS	Domain Name Service
HTML	Hyper Text Markup Language
HTTP	Hyper Text Transfer Protocol
IETF	Internet Engineering Task Force
IP	Internet Protocol
ISP	Internet Service Provider
L2TP	Layer 2 Tunnelling Protocol
LSP	Label Switched Path
MPLS	Multiprotocol Label Switching
NP	Non-deterministic Polynomial
ODN	Overlay Distribution Network
OSPF	Open Shortest Path First
POP	Point of Presence
RAM	Random Access Memory
RFC	Request for Comments
RTT	Round Trip Time
QoS	Quality of Service
TCP	Transmission Control Protocol

TTL	Time To Live
UDP	User Datagram Protocol
VoD	Video on Demand
VPN	Virtual Private Network