



Doctoral Thesis

WORD-METRIC-BASED GREEDY ROUTING
FOR CAYLEY GRAPHS

DANIELA AGUIRRE GUERRERO

2018



Doctoral Thesis

WORD-METRIC-BASED GREEDY ROUTING
FOR CAYLEY GRAPHS

DANIELA AGUIRRE GUERRERO

2018

Doctoral Program in Technology

Supervised by:

Dr. Pere Vilà Talleda and Dr. Lluís Fàbrega Soler

Thesis submitted to the University of Girona in fulfillment of the
requirements for the degree of Doctor of Philosophy

CERTIFICAT DE DIRECCIÓ DE TESI

Dr. Pere Vilà Talleda and Dr. Lluís Fàbrega Soler, del Departament d'Arquitectura i Tecnologia de Computadors de la Universitat de Girona,

DECLAREM:

Que el treball titulat *Word-Metric-based Greedy Routing for Cayley Graphs*, que presenta Daniela Aguirre Guerrero per a l'obtenció del títol de doctor, ha estat realitzat sota la nostra direcció i que compleix els requisits per poder optar a Menció Internacional.

I, perquè així consti i tingui els efectes oportuns, signem aquest document.

Girona, Juliol 2018

Dr. Pere Vilà Talleda

Dr. Lluís Fàbrega Soler

ACKNOWLEDGMENTS

PUBLICATIONS

The work developed in this thesis led to the following publications:

JOURNAL ARTICLES

- [1] **D. Aguirre-Guerrero**, M. Camelo, P. Vilà and Ll. Fàbrega, "WMGR: A Generic and Compact Routing Scheme for Data Center Networks," in *IEEE/ACM Transactions on Networking*, vol. 26, no. 1, pp. 356-369. Feb. 2018. DOI: 10.1109/TNET.2017.2779866

PEER-REVIEWED CONFERENCES AND WORKSHOPS

- [1] **D. Aguirre-Guerrero**, M. Camelo, P. Vilà and Ll. Fàbrega, "Compact Greedy Routing in Large-scale Networks using Word-metric Spaces," *1st. International Workshop on Elastic Networks Design and Optimization*, Cartagena, Spain, 2016.

OTHER CONFERENCES AND WORKSHOPS

- [1] **D. Aguirre-Guerrero**, P. Vilà and Ll. Fàbrega, "Encaminamiento de Información en Redes Comunicación de Gran Escala," *6to. Simposio de Becarios CONACyT en Europa*, Strasbourg, France 2017.
- [2] **D. Aguirre-Guerrero**, P. Vilà and Ll. Fàbrega, "Greedy Geometric in Word Metric Spaces," *1st. Conference of Pre-doctorals Researches*, Girona, Spain, 2016. ISBN: 978-8-48458-502-2

LIST OF FIGURES

LIST OF TABLES

LIST OF ALGORITHMS

ACRONYMS

WMGR word-metric based greedy routing

CONTENTS

I	PRELIMINARIES	1
1	INTRODUCTION	2
1.1	Motivation	2
1.2	Problem Statement	2
1.3	Objectives	2
1.4	Contributions	2
1.5	How to Read this Thesis	2
2	THEORETICAL FRAMEWORK	3
2.1	Graph Theory	3
2.2	Finite State Automata	3
2.2.1	Regular Languages	3
2.2.2	2-variable Finite State Automata	3
2.2.3	Existential Quantification	3
2.3	Group Theory	3
2.3.1	Finitely Presented Groups	3
2.3.2	Group Homomorphism	3
2.3.3	Abelian Groups	3
2.3.4	Cayley Graphs	3
2.4	Automatic Groups	3
2.4.1	Automatic Structures	3
2.4.2	Words as Nodes and Paths	3
2.4.3	Solving the Shortest Path Problem in Cayley Graphs	3
3	CAYLEY GRAPHS: APPLICATIONS AND ROUTING ALGORITHMS	4
3.1	Topological Properties of Cayley Graphs	4
3.2	Applications	4
3.2.1	Interconnection Networks	4
3.2.2	Error Correcting Codes	4
3.2.3	Hash Functions	4
3.3	Routing Algorithms	4
3.3.1	Performance Metrics	4
3.3.2	Sims Factoring Algorithm	4
3.3.3	Permutation-sort Algorithm	4
3.3.4	Routing Algorithm for Boreal Cayley Graphs	4
II	WORD-METRIC-BASED GREEDY ROUTING	5
4	PATH COMPUTATION IN CAYLEY GRAPHS	6
4.1	Distributed Configuration	6
4.2	Computing the Shortest Path	6
4.3	Computing the K-Shortest Paths	6
4.4	Computing the Shortest Node-disjoint Shortest Paths	6
4.5	Computing the Shortest Edge-disjoint Shortest Paths	6
5	FAULT-TOLERANT ROUTING IN CAYLEY GRAPHS	7
5.1	Multiple-node Failures	7
5.1.1	Computing the Shortest Path Avoiding a Set of Nodes	7
5.1.2	Node-failure Notification	7

5.1.3	Node-failure Recovery	7
5.2	Multiple-edge Failures	7
5.2.1	Computing the Shortest Path Avoiding a Set of Edges	7
5.2.2	Edge-failure Notification	7
5.2.3	Edge-failure Recovery	7
6	PERFORMANCE EVALUATION	8
6.1	Stretch	8
6.2	Space Requirements	8
6.2.1	Node Label	8
6.2.2	Automatic Structures	8
6.3	Forwarding Decision Time	8
6.3.1	Source Routing	8
6.3.2	Hop-by-hop Routing	8
6.4	Convergence Time of Fault-tolerant Routing	8
6.5	Message Complexity	8
6.5.1	Node Label Assignment	8
6.5.2	Failures Notification	8
6.5.3	Recovery Notification	8
7	CONCLUSIONS	9
7.1	Summary of Completed Work	9
7.2	Review of Contributions	9
7.3	Future Work	9
	Appendix	10

ABSTRACT

Since word-metric based greedy routing ([WMGR](#)) *a priori* (e.g., exploring confined natural environments like underwater caves). In these scenarios, [WMGRs](#)

RESUMEN

Desde

RESUM

Des

Part I

PRELIMINARIES

You can put some informational part preamble text here. Illo principalmente su nos. Non message *occidental* angloromanic da. Debitas effortio simplificate sia se, auxiliar summarios da que, se avantiate publicationes via. Pan in terra summarios, capital interlingua se que. Al via multo esser specimen, campo responder que da. Le usate medical addresses pro, europa origine sanctificate nos se.

INTRODUCTION

1.1 MOTIVATION

1.2 PROBLEM STATEMENT

1.3 OBJECTIVES

1.4 CONTRIBUTIONS

1.5 HOW TO READ THIS THESIS

THEORETICAL FRAMEWORK

2.1 GRAPH THEORY

2.2 FINITE STATE AUTOMATA

2.2.1 *Regular Languages*

2.2.2 *2-variable Finite State Automata*

2.2.3 *Existential Quantification*

2.3 GROUP THEORY

2.3.1 *Finitely Presented Groups*

2.3.2 *Group Homomorphism*

2.3.3 *Abelian Groups*

2.3.4 *Cayley Graphs*

2.4 AUTOMATIC GROUPS

2.4.1 *Automatic Structures*

2.4.2 *Words as Nodes and Paths*

2.4.3 *Solving the Shortest Path Problem in Cayley Graphs*

CAYLEY GRAPHS: APPLICATIONS AND ROUTING ALGORITHMS

3.1 TOPOLOGICAL PROPERTIES OF CAYLEY GRAPHS

3.2 APPLICATIONS

3.2.1 *Interconnection Networks*

3.2.1.1 *Processor Interconnection Networks*

3.2.1.2 *Data Center Networks*

3.2.1.3 *Wireless Sensor Networks*

3.2.2 *Error Correcting Codes*

3.2.3 *Hash Functions*

3.3 ROUTING ALGORITHMS

3.3.1 *Performance Metrics*

3.3.2 *Sims Factoring Algorithm*

3.3.3 *Permutation-sort Algorithm*

3.3.4 *Routing Algorithm for Boreal Cayley Graphs*

Part II

WORD-METRIC-BASED GREEDY ROUTING

You can put some informational part preamble text here. Illo principalmente su nos. Non message *occidental* angloromanic da. Debitas effortio simplificate sia se, auxiliar summarios da que, se avantiate publicationes via. Pan in terra summarios, capital interlingua se que. Al via multo esser specimen, campo responder que da. Le usate medical addresses pro, europa origine sanctificate nos se.

PATH COMPUTATION IN CAYLEY GRAPHS

4.1 DISTRIBUTED CONFIGURATION

4.2 COMPUTING THE SHORTEST PATH

4.3 COMPUTING THE K-SHORTEST PATHS

4.4 COMPUTING THE SHORTEST NODE-DISJOINT SHORTEST PATHS

4.5 COMPUTING THE SHORTEST EDGE-DISJOINT SHORTEST PATHS

FAULT-TOLERANT ROUTING IN CAYLEY GRAPHS

5.1 MULTIPLE-NODE FAILURES

5.1.1 *Computing the Shortest Path Avoiding a Set of Nodes*

5.1.2 *Node-failure Notification*

5.1.3 *Node-failure Recovery*

5.2 MULTIPLE-EDGE FAILURES

5.2.1 *Computing the Shortest Path Avoiding a Set of Edges*

5.2.2 *Edge-failure Notification*

5.2.3 *Edge-failure Recovery*

PERFORMANCE EVALUATION

6.1 STRETCH

6.2 SPACE REQUIREMENTS

6.2.1 *Node Label*

6.2.1.1 *Source Routing*

6.2.1.2 *Hop-by-hop Routing*

6.2.2 *Automatic Structures*

6.3 FORWARDING DECISION TIME

6.3.1 *Source Routing*

6.3.2 *Hop-by-hop Routing*

6.4 CONVERGENCE TIME OF FAULT-TOLERANT ROUTING

6.5 MESSAGE COMPLEXITY

6.5.1 *Node Label Assignment*

6.5.2 *Failures Notification*

6.5.3 *Recovery Notification*

CONCLUSIONS

7.1 SUMMARY OF COMPLETED WORK

This thesis has addressed the problem of

7.2 REVIEW OF CONTRIBUTIONS

7.3 FUTURE WORK

APPENDIX