

**ENERGY EFFICIENT AND LOW-LATENCY
COMMUNICATIONS FOR FUTURE
WIRELESS NETWORKS**

by
Tien Thai VU

Dissertation submitted in fulfilment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

under the supervision of

Principal supervisor: Dr. Diep N. Nguyen
and Co-supervisors:
Dr. Hoang Dinh
Prof. Eryk Dutkiewicz

School of Electrical and Data Engineering
University of Technology Sydney
Sydney, Australia

August 2021

ABSTRACT

The ever-growing number of smart and mobile devices as well as their emerging applications call for novel solutions to address new challenges in energy efficiency and latency requirements. This thesis aims to develop novel protocols, resource allocation algorithms, and network architectures to enable low-latency services for mobile devices and applications (e.g., mission-critical applications in intelligent transportation systems, healthcare, gaming, and virtual/augmented reality applications). Specifically, we first introduce proactive resource allocation approaches to reduce the communications delay in machine type communications. Exploiting the correlation between smart devices (e.g., sensors), we propose an algorithm to proactively allocate uplink resources for these devices, and thereby reducing the expected uplink delay. Second, to address the energy efficiency problem for hardware-constrained devices, we propose a multi-tier task-offloading network architecture. In this novel network architecture, computation tasks from these devices can be offloaded to a network of computation-aiding servers or fog/edge nodes to minimize the energy consumption subject to the delay constraints of services. Because computing resources on fog nodes are usually limited, while task offloading demands from user devices are high, we develop an unprecedented model, allowing fog nodes and a powerful cloud server to collaborate to meet all tasks' requirements. Our experimental results demonstrate that the proposed solution can attain the optimal energy efficiency while meeting strict latency requirements for all devices and computing tasks. Finally, to address the fairness in allocating commu-

nication and computation resources of heterogeneous fog nodes for mobile devices considering diverse requirements (i.e., delay, security, and application compatibility), we adopt the proportional fairness criterion to develop a joint task offloading and resource allocation solution. The experimental results (i.e., fairness indexes, energy benefit, and energy consumption) show that the proposed scheme can attain the maximum proportional fairness in terms of the energy benefit (from offloading to fog nodes).

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Tien Thai VU, declare that this thesis is submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy, in the School of Electrical and Data Engineering, Faculty of Engineering and Information Technology, at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference of acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program and the Ministry of Education and Training (MOET) – Vietnam.

Name of Student: Tien Thai VU

Production Note:
Signature of Student: Signature removed prior to publication.

Date: 05 August 2021

ACKNOWLEDGMENTS

First and foremost, I am so much indebted to my beloved wife and children, who are always with me during this course. Completing this Ph.D. degree would not be possible without their love and immense support. I also want to thank my dear parents, sisters, and relatives for their continuous encouragement and support.

I would like to express my sincerest gratitude to my principal supervisor, Dr. Diep N. Nguyen (University of Technology Sydney, Australia), who has helped me through some difficulties during my Ph.D. studies. He has been always encouraged me to strive for excellence in my career. This work would not have been completed without his mentoring, patience, motivation, and unflinching support. Sincere thanks are also extended to my co-supervisors Dr. Hoang Dinh and Prof. Eryk Dutkiewicz for their kindness, support, advice, and encouragement throughout this research.

I also acknowledge the staff of the School of Electrical and Data Engineering as well as the Graduate Research School for their immense support during the difficult time of my studies.

I acknowledge the Vietnamese Government Scholarship (VIED scholarship) for the financial support towards this research. I also acknowledge the UTS-VIED scholarship for the supplement to the VIED scholarship.

Finally, to all my friends, thank you for your advice and encouragement in many times of crisis. Your friendship makes my life a wonderful experience. I cannot list all the names here, but you are always on my mind.

Contents

Abstract	iii
Acknowledgments	ix
Table of Contents	xi
List of Figures	xv
List of Tables	xix
List of Publications	xxi
1 INTRODUCTION AND LITERATURE REVIEW	1
1.1 Literature Review and Motivations	2
1.1.1 Low Latency Communications	2
1.1.2 Energy Efficiency in Fog Computing	3
1.1.3 Fairness in Fog Computing Resource Allocation	5
1.2 Contributions	7
1.2.1 2D Proactive Uplink Resource Allocation Algorithm for Event- Based MTC Applications	7
1.2.2 Optimal Energy Efficiency with Delay Constraints for Multi- layer Cooperative Fog Computing Networks	8

1.2.3	Proportional Fairness for Fog Computing Resource Allocation using Dynamic Branch-and-Bound Benders Decomposition Algorithm	10
1.3	Organization of the Thesis	12
2	2D Proactive Uplink Resource Allocation Algorithm for Event-Based MTC Applications	15
2.1	System Model	16
2.2	2D Proactive Uplink Resource Allocation Algorithm	18
2.2.1	2D Proactive Uplink Resource Allocation	18
2.2.2	2D Predictive Uplink Resource Allocation Algorithm	21
2.2.3	Complexity Analysis	21
2.2.4	Optimal Ring Width d_0	24
2.3	Performance Analysis of 2D-PURA	25
2.4	Numerical Results	28
2.5	Conclusion	32
3	Optimal Energy Efficiency with Delay Constraints for Multi-layer Cooperative Fog Computing Networks	35
3.1	System Model and Problem Formulation	36
3.1.1	Network Model	36
3.1.2	Problem Formulation	40
3.2	Proposed Optimal Solutions	43
3.2.1	Convexity of Relaxed Problems	43
3.2.2	Improved Branch and Bound Algorithm	44
3.2.3	Feasibility-Finding Benders Decomposition	48
3.2.4	Implementation Protocol and Complexity Analysis	61
3.3	Performance Evaluation	64
3.3.1	Offloading Analysis	64

3.3.2	Experiment Setup	65
3.3.3	Numerical Results	67
3.4	Conclusion	77
4	Proportional Fairness for Fog Computing Resource Allocation	79
4.1	System Model and Problem Formulation	80
4.1.1	System Model	80
4.1.2	Task Execution	81
4.1.3	Problem Formulation	85
4.2	Proposed Optimal Solutions	88
4.2.1	Convexity of Relaxed Problem	88
4.2.2	Dynamic Branch-and-Bound Benders Decomposition	89
4.2.3	Distributed Solving Subproblems	90
4.2.4	Cutting-Plane Generation	94
4.2.5	Solving the Master Problem	95
4.2.6	DBBD Procedure	101
4.2.7	Complexity Analysis	103
4.3	Performance Evaluation	106
4.3.1	Experiment Setup	106
4.3.2	Numerical Results	108
4.4	Conclusion	119
5	CONCLUSIONS AND FUTURE WORK	121
5.1	Innovations in this Thesis	121
5.1.1	Low Latency Communications	121
5.1.2	Energy Efficiency Fog Computing Resource Allocation	122
5.1.3	Fairness for Fog Computing Resource Allocation	122
5.2	Future Work	123
5.2.1	Machine Learning for Proactive Resource Allocation	123

5.2.2	Age of Information in Mobile Edge Computing Resource Allocation	123
5.2.3	AI-Empowered Mobile Edge Computing	123
5.2.4	Online Learning to Estimate Parameters for Proactive Resource Allocation	124
A	Proofs of Theorems in Chapter 3	125
A.1	Proof of Theorem 1	125
A.2	Proof of Theorem 2	125
A.3	Proof of Lemma 1	126
A.4	Proof of Theorem 3	126
A.5	Proof of Theorem 4	126
B	Proofs of Theorems in Chapter 4	129
B.1	Proof of Theorem 5	129
B.2	Proof of Theorem 6	130
B.3	Proof of Theorem 7	130
B.4	Proof of Theorem 8	130
B.5	Proof of Theorem 9	131
	Abbreviations	133
	Bibliography	137

List of Figures

2.1	MTC communications under a cellular network model.	18
2.2	2D Predictive resource allocation model.	19
2.3	2D Predictive uplink resource allocation algorithm.	22
2.4	SR saving due to successful predictions for the 2D-PURA algorithm when the period $\sigma = 40$ subframes and the ring-crossing time τ_0 is increased.	29
2.5	Uplink resource wastage due to unsuccessful predictions for the 2D- PURA algorithm when the period $\sigma = 40$ subframes and the ring- crossing time τ_0 is increased.	30
2.6	Mean uplink delay for the 2D-PURA algorithm when the period $\sigma =$ 40 subframes and the ring-crossing time τ_0 and the threshold y are varied.	31
2.7	A comparison of mean uplink delay for the 2D-PURA algorithm, the 1D algorithm, and the standard method when the period $\sigma = 40$ subframes.	32
3.1	Three-layer cooperative fog computing network.	37
3.2	Search Tree for the IBBA algorithm with Optimal Solution Selection.	47
3.3	Feasibility-Finding Benders Decomposition Model.	50
3.4	Feasibility-Finding Benders Decomposition Procedure.	51
3.5	Protocol defining the operation of proposed algorithms.	61

3.6	Percentage of offloaded tasks and error rate as the task complexity α_i is increased.	69
3.7	Average consumed energy at mobile devices as the task complexity α_i is increased.	69
3.8	Average task processing delay as the task complexity α_i is increased.	70
3.9	Percentage of offloaded tasks and error rate as the delay requirement t_i^r is less strict.	72
3.10	Average consumed energy at mobile devices as the delay requirement t_i^r is less strict.	73
3.11	Percentage of offloaded tasks and average delay as the backhaul capacity W_j^c increases.	74
3.12	Computation time and number of solved intermediate problems in order to find an optimal solution when the task complexity α_i is increased.	76
3.13	Computation time and the number of solved intermediate problems to find an optimal solution when the delay requirement t_i^r is less strict.	76
4.1	Three-layer cooperative fog computing network.	81
4.2	Dynamic Branch-and-Bound Benders Decomposition.	89
4.3	Jain's index and Min-Max Ratio of energy benefits as the number of devices N is increased.	110
4.4	Total consumed energy and energy benefits as the number of devices N is increased.	110
4.5	Jain's index and Min-Max Ratio of energy benefits as the fog nodes' resources are increased.	112
4.6	Total consumed energy and energy benefits as the fog nodes' resources are increased.	113
4.7	Jain's index and Min-Max Ratio of energy benefits as the fog nodes' resources are increased while devices' configurations are the same. . .	114

4.8	Total consumed energy and energy benefits as the fog nodes' resources are increased while devices' configurations are the same.	115
4.9	Jain's index and Min-Max Ratio of energy benefits as the number of tasks is increased.	116
4.10	Total consumed energy and energy benefits as the number of tasks is increased.	117
4.11	The number of tasks offloaded to each fog node as the number of tasks is increased.	117
4.12	The average delay of tasks as the number of tasks is increased.	118

List of Tables

2.1	Experimental parameters	28
3.1	Experimental parameters	66
3.2	Complexity and computation times	78
4.1	Categories of tasks according to energy benefits and QoS satisfaction.	84
4.2	Experimental parameters	107

List of Publications

Journal publications

- **Tien Thai VU**, Diep N. Nguyen, Dinh Thai Hoang, Eryk Dutkiewicz, and Thuy V. Nguyen, “Optimal energy efficiency with delay constraints for multi-layer cooperative fog computing networks”, in *IEEE Transactions on Communications*, 2021. (related to Chapter 3)
- “Proportional fairness for fog computing resource allocation”, in *IEEE Transactions on Mobile Computing*, 2021 (under submission). (related to Chapter 4)

Conference publications

- **Tien Thai VU**, Diep N. Nguyen, and Eryk Dutkiewicz, “2D proactive uplink resource allocation algorithm for event based MTC applications”, in *2018 IEEE Wireless Communications and Networking Conference (WCNC)*, 2018. (related to Chapter 2)
- **Tien Thai VU**, Nguyen Van Huynh, Dinh Thai Hoang, Diep N. Nguyen, and Eryk Dutkiewicz, “Offloading energy efficiency with delay constraint for cooperative mobile edge computing networks”, in *2018 IEEE Global Communications Conference (GLOBECOM)*, 2018. (related to Chapter 3)

- **Tien Thai VU**, Diep N. Nguyen, Dinh Thai Hoang, and Eryk Dutkiewicz, “QoS-aware fog computing resource allocation using feasibility-finding benders decomposition”, in *2019 IEEE Global Communications Conference (GLOBECOM)*, 2019. (related to Chapter 3)
- “Proportional fairness fog computing resource allocation using dynamic branch-and-bound benders decomposition algorithm”, in *2022 IEEE Wireless Communications and Networking Conference (WCNC)*, 2022 (under submission). (related to Chapter 4)