Energy conservation in distributed heterogeneous computing environments using economic resource allocation mechanisms

by

Timothy Michael Lynar
BIT(Hons)

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

Doctor of Philosophy

The University of Newcastle

June, 2011
This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968.

Signature

Date
Abstract

Energy conservation in distributed heterogeneous computing environments using economic resource allocation mechanisms

by Timothy Michael Lynar

This thesis examines the question: can economic resource allocation mechanisms be used in distributed computing environments to reduce energy consumption whilst maintaining execution speed? This thesis investigates the use of several resource allocation mechanisms that take account of the power consumption and processing capacity of each available computing node within a distributed heterogeneous computing environment. Different economic resource allocation mechanisms have different attributes and allocate resources differently. The resource allocation mechanisms are evaluated to examine their effect on the time and energy required to process a workload of the sort that might be expected in a distributed computing system. Initial examination of the resource allocation mechanisms was conducted through the execution of artificial workloads on a simulated cluster. To further this research, a real cluster and grid environment was created from obsolete computers. An examination was undertaken of the use of obsolete computers in distributed computing environments and how the use of such systems may assist to mitigate electronic waste. The examination of resource allocation was continued on a cluster, and then on an institutional grid. The simulation model was then calibrated to the cluster and grid, which was then used to simulate the execution of real published grid workloads under each of the resource allocation mechanisms. The resource allocation mechanisms under consideration were found to have different characteristics that resulted in them being suited for different types of workload. It was also found that the choice of a resource allocation mechanism that takes account of the power consumption and performance of individual resources can make a significant difference, through leveraging the heterogeneous nature of resources, to the total system energy consumed and time taken in computing a workload.
TABLE OF CONTENTS

Abstract iii

List of Figures xi

List of Tables xiii

List of abbreviations xix

Publications from this Research xxi

Chapter 1: Introduction 1
  1.1 Overview and purpose .................................. 1
  1.2 Structure ............................................... 2
  1.3 Key contributions ..................................... 9
  1.4 Definition of key terms ................................ 12

Chapter 2: Literature review 15
  2.1 Introduction ........................................... 15
  2.2 Agent-based models .................................... 15
  2.3 Resource allocation mechanisms in distributed computing environments . 20
  2.4 Electronic waste ........................................ 29
  2.5 Computing projects that utilise e-waste .................. 37
  2.6 Green high-performance computing and resource allocation ............ 38
  2.7 Benchmarks ............................................ 46
  2.8 Concluding remarks .................................... 48
### Chapter 3: Performance efficiency metric: an analysis of the use of different metrics to rank nodes

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Introduction</td>
<td>51</td>
</tr>
<tr>
<td>3.2 Description of performance efficiency metrics</td>
<td>53</td>
</tr>
<tr>
<td>3.3 Analysis of metrics</td>
<td>54</td>
</tr>
<tr>
<td>3.4 Methodology</td>
<td>56</td>
</tr>
<tr>
<td>3.5 Results</td>
<td>62</td>
</tr>
<tr>
<td>3.6 Discussion</td>
<td>64</td>
</tr>
<tr>
<td>3.7 Concluding remarks</td>
<td>70</td>
</tr>
</tbody>
</table>

### Chapter 4: Energy aware resource allocation: a simulation study of the use of economic resource allocation techniques to reduce energy consumption

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Introduction</td>
<td>73</td>
</tr>
<tr>
<td>4.2 Simulation details</td>
<td>74</td>
</tr>
<tr>
<td>4.3 Description of resource allocation mechanisms</td>
<td>77</td>
</tr>
<tr>
<td>4.4 Methodology</td>
<td>88</td>
</tr>
<tr>
<td>4.5 Results</td>
<td>89</td>
</tr>
<tr>
<td>4.6 Discussion</td>
<td>93</td>
</tr>
<tr>
<td>4.7 Concluding remarks</td>
<td>98</td>
</tr>
</tbody>
</table>

### Chapter 5: Creating the test platforms: distributed computing environments constructed from electronic waste

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Introduction</td>
<td>101</td>
</tr>
<tr>
<td>5.2 The cluster test platform</td>
<td>102</td>
</tr>
<tr>
<td>5.3 Electronic waste and environmental costs</td>
<td>103</td>
</tr>
<tr>
<td>5.4 High-performance computing from e-waste resources</td>
<td>104</td>
</tr>
<tr>
<td>5.5 Advantages of using e-waste resources</td>
<td>105</td>
</tr>
<tr>
<td>5.6 Limitations of using e-waste resources</td>
<td>107</td>
</tr>
<tr>
<td>5.7 Examination of the cluster</td>
<td>109</td>
</tr>
<tr>
<td>5.8 Discussion</td>
<td>112</td>
</tr>
<tr>
<td>5.9 Concluding remarks</td>
<td>113</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

3.1 Energy consumption for workflow 14 ........................................ 65
3.2 Energy consumption for workflow 6 ........................................ 67
3.3 Energy consumption for workflow 7 ........................................ 68
3.4 Energy consumption for workflow 8 ........................................ 69
4.1 A class diagram of the simulation model ................................ 76
4.2 Number of tasks submitted per day in the DAS-2 grid trace ........ 86
4.3 Computation required per day in the DAS-2 grid trace .............. 87
4.4 Computation required in a one-day section of the DAS-2 grid trace 92
4.5 Computation required in the first hour of a section of the DAS-2 grid trace 93
4.6 Task submission in the one-day section of the DAS-2 grid trace .... 94
4.7 Energy consumption in the one-day section of the DAS-2 grid trace 95
5.1 Results of a performance test ................................................. 111
5.2 Power usage results for the individual node and for the cluster .... 112
6.1 UML Activity diagram describing the resource allocation application 120
6.2 Setup of the cluster tests ..................................................... 127
6.3 Setup of the grid tests ......................................................... 128
6.4 Setup of the cluster environment ........................................... 130
6.5 Setup of the grid environment ............................................. 131
8.1 Number of tasks submitted per day in LCG grid trace .............. 167
E.1 Class diagram of the performance efficiency metric simulation .... 218
### LIST OF TABLES

3.1 Node performance results ........................................ 55
3.2 Node performance results as ranks .............................. 56
3.3 Parameter values for test workflows ............................ 62
3.4 Results from simulation ........................................ 63
4.1 Inputs from real nodes ........................................... 80
4.2 Basic computational workflows with homogeneous tasks .... 85
4.3 Workflows with a constant number of identical jobs .......... 85
4.4 Single-hit workflows where tasks are submitted only at the first time step . 86
4.5 Time and energy performance results relative to CRA ........ 90
4.6 Results shown as a percentage when utilising VOVO ........ 91
5.1 Nodes used in the e-waste cluster ............................... 103
6.1 Performance metrics used in tests of the resource allocation application . 118
6.2 Basic computational workflows with homogeneous tasks .... 124
6.3 Matrix of tests .................................................... 126
6.4 Attributes of cluster test nodes ................................ 129
6.5 Attributes of grid nodes .......................................... 131
6.6 Summary of cluster results ...................................... 132
6.7 Summary of grid results .......................................... 133
6.8 Summary of relative cluster results ............................ 136
6.9 Summary of relative grid results ................................ 142
ACKNOWLEDGMENTS

Thank you to my supervisors Dr. Ric Herbert and Dr. William Chivers, for their help and encouragement; to the Blue Gum Flats research group for their encouragement; to Simon for the help and direction he provided, and for assistance with English expression. Thank you to Steve Owers and Gary Maynard for their assistance in acquiring space and equipment. Thank you to Nic Croce and Maureen Townley-Jones from the Statistical Support Service from the Faculty of Science and Information Technology for their time and statistical advice. My sincere thanks to Rod Bell for providing invaluable feedback on this thesis. I acknowledge the help of a professional thesis editor Belinda Leskiw.
DEDICATION

To my wife Rachel,
who provided the most encouragement and support of all.
LIST OF ABBREVIATIONS

BA: Batch auction

CDA: Continuous double auction

CLUSTER: Computing cluster

CRA: Continuous random allocation

DVFS: Dynamic voltage and frequency scaling

EOE: End of execution

E-WASTE: Electronic waste

FLOPS: Floating point operations per second

FOSS: Free and open source software

GT: Grid trace

HPC: High-performance computing

HPDC: High-performance distributed computing

HPL: High-performance Linpack benchmark

MFLOPS: Millions of floating point operations per second
MIM: Marginal increase mechanism

MPI: Message passing interface

MWIPS: Millions of whetstone instructions per second

NODE: Computing node

PPBA: Pre-processed batch auction

PXE: Pre-execution environment

SPMD: Single process, multiple data

TTT: Test task time

UML: Unified modelling language

VFS: Voltage and frequency scaling

VOVO: Variable-on variable-off

WF: Workflow

WIPS: Whetstone instructions per second

ZIT: Zero intelligence trader
PUBLICATIONS RESULTING FROM THIS RESEARCH

*Fully refereed journal articles*


*Fully refereed conference proceedings*


