Coordination mechanisms for self-interested multi-agent systems

Q. Bai
University of Wollongong, quan@uow.edu.au

Recommended Citation
Coordination Mechanisms for Self-interested Multi-agent Systems

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

Doctor of Philosophy

from

UNIVERSITY OF WOLLONGONG

by

Quan Bai
Computer Science Department
April 2007
Dedicated to

my parents and wife
Declaration

This is to certify that the work reported in this thesis was done by the author, unless specified otherwise, and that no part of it has been submitted in a thesis to any other university or similar institution.

________________________________________
Quan Bai
April 30, 2007
A multi-agent system (MAS) is a collection of agents that interact with each other. Multi-agent systems (MASs) can be classified as self-interested MASs and cooperative MASs according to the features of agent goals. Coordination is one of the major issues of MAS research. It plays a central role in MASs to ensure agents achieve interactions properly. Today, the remarkable growth of MAS applications brings higher requirements and more challenges to agent coordinations. Many complex applications require a MAS to include various agents to work together under an open and dynamic environment.

Toward some challenges in current agent coordination research, this thesis deeply investigates agent coordination problems in self-interested MASs, and proposes three coordination mechanisms based on three different methodologies. Firstly, this thesis investigates the use of Coloured Petri Net techniques in agent coordinations. As one of the best modelling tools, Coloured Petri Nets can express a great range of concurrent systems and interactions in graphical representations and well-defined semantics, and allow formal analysis and transformations. In the thesis, a coordination mechanism that uses Coloured Petri Nets to model interaction protocols of agents is proposed and implemented. This mechanism allows interaction protocols to be separated from hard-coded agents. The separation of agents and interaction protocols makes it possible to allow agents to evaluate and select protocols before they operate interactions. Furthermore, a Coloured Petri
Net based approach that allows agents to propose, exchange and evaluate interaction protocols is also introduced in this thesis. By citing Coloured Petri Net techniques in agent coordinations, agents have more flexible and rational interactions. Secondly, this thesis proposes a flexible team formation mechanism for self-interested agents. In this mechanism, agents can evaluate the performance and importance of other agents in the system, and select team members with reasonable terms and costs according to the evaluation result automatically. Comparing with some traditional team formation mechanisms, the flexible team formation mechanism makes agent team compositions more reasonable, and avoids some potential benefit conflicts among self-interested team members (more suitable for self-interested agents). Finally, a knowledge level coordination mechanism that uses of ontologies to describe and manage MAS knowledge is introduced in this thesis. By using ontologies, MAS knowledge can be described and organised in hierarchies, and the dynamic features of independent knowledge sources are captured.
Acknowledgements

Ph.D study is a long journey that could never have been completed without the help of many people.

First and foremost, I would like to thank my supervisor, Associate Professor Minjie Zhang, for her continuous encouragement, patience, and support throughout my Ph.D studies. She is the person who opened the door to academic research for me. Her research knowledge and technical advice have been essential in the completion of this thesis.

I am very grateful to Professor John Fulcher for giving me many helpful suggestions and providing me a chance to apply my knowledge into real applications. My thanks also go to many people in my school for always giving me helps over the years.

My thanks also go to my friends at University of Wollongong, especially the members of my group, Hui Yang, Kaiyu Song, Jia Tang and Fenghui Ren. They make my life in Wollongong so memorable.

On the personal front, I would express my deepest gratitude and love to my parents. I owned them too much in the years of my Ph.D study. I also want to thank my sister and her daughter. If they have not been taking care of my parents, I would never concentrate on my studies. Most important of all, I would like to thank my wife, Wenwei Yan, for her unquestionable support and understanding throughout the years. Her unreserved love makes it possible for me to finish this thesis.
I would like to thank the University of Wollongong for providing me a University Postgraduate Award. I also want to thank the School of IT and Computer Science for the financial supports towards attending research conferences.

Finally, my thanks also go to my examiners, for their valuable suggestions and comments which have been most helpful for improving the quality of this thesis.
The followings are a list of my research papers that have been published or accepted during my Ph.D study that is to end by the completion of this thesis.


• Quan Bai and Minjie Zhang, Agent Coordination Through Ontology Man-
agments. In Proceedings of International Conference on Artificial Intelli-

• Quan Bai and Minjie Zhang, SWOAM - A Semantic Web Based Online
Auction Multi-agent System. In Proceedings of the International Con-
ference on Intelligent Agents, Web Technologies and Internet Commerce

• Quan Bai, Minjie Zhang, and Khan Thin Win, A Coloured Petri Net Based
International Conference on Autonomous Robots and Agents, pages 152-

• Quan Bai, Wei Li, and Minjie Zhang, A Computational Strategy for Infor-
mation Integration in Meta-Search Agent Systems. In Proceedings of In-
ternational Conference on Information and Knowledge Engineering, pages

• Quan Bai, Wei Li, Minjie Zhang, and Kaiyu Song, A Fuzzy Logic Based
Strategy for Information Integration in Meta-Search Agent Systems. In Proceeding of the Fourth International Symposium on Knowledge and Sys-

• Quan Bai and Minjie Zhang, An Ontology Based Multi-agent Online Auc-
tion System. In Proceeding of the Fourth International Conference on In-
# Contents

Abstract vi

Acknowledgements viii

Publications x

1 Introduction 1

1.1 Agents and Agent Interactions 3

1.2 Multi-agent Systems 5

1.3 Self-interested and Cooperative Multi-agent Systems 7

1.3.1 Traditional Classification 7

1.3.2 The Blurring Boundary 8

1.4 Agent Coordination in Multi-agent Systems 9

1.4.1 Classification of Coordination Techniques 10

1.4.2 Objective Coordination Mechanisms 11

1.5 Challenges in Multi-agent Coordination 11

1.6 Research Objectives and Major Contributions of the Thesis 13

1.7 Thesis Organisation 15

2 Related Research and Literature Review 18

2.1 Distinctions between Objective and Subjective Coordination 19

2.2 Agent Communication in Multi-Agent Systems 20
2.2.1 Agent Communication Language . . . . . . . . . . . . . . 21
2.2.2 Communication Infrastructure . . . . . . . . . . . . . . . 23
2.2.3 Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . 27
2.3 Knowledge and Ontology of Multi-Agent Systems . . . . . . . . 27
  2.3.1 Ontology in Multi-Agent Systems . . . . . . . . . . . . . 28
  2.3.2 Ontology Languages . . . . . . . . . . . . . . . . . . . . 28
  2.3.3 Knowledge and Ontology Services . . . . . . . . . . . . . 29
  2.3.4 Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . 32
2.4 Coordination through Contracting . . . . . . . . . . . . . . . . . 33
  2.4.1 The Contract Net Protocol . . . . . . . . . . . . . . . . . . 33
  2.4.2 The Contingency Contract . . . . . . . . . . . . . . . . . . 35
  2.4.3 The Leveled Commitment Contract . . . . . . . . . . . . . 36
2.5 Organisational Coordination . . . . . . . . . . . . . . . . . . . . . 37
  2.5.1 Organisations with Centralised Controls . . . . . . . . . 38
  2.5.2 Inclusion of Middle-Agents in Agent Organisations . . . . 39
  2.5.3 Self-Organising Mechanisms . . . . . . . . . . . . . . . . . 40
  2.5.4 Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . 41
2.6 A Summary of Literature Review . . . . . . . . . . . . . . . . . . 41

3 Coloured Petri Net Based Approaches for Coordinating Agent
  Interactions and Negotiations . . . . . . . . . . . . . . . . . . . . . 43
  3.1 Petri Net and Coloured Petri Net . . . . . . . . . . . . . . . . . 46
    3.1.1 Petri Net . . . . . . . . . . . . . . . . . . . . . . . . . . 46
    3.1.2 Coloured Petri Net . . . . . . . . . . . . . . . . . . . . . 48
  3.2 Related Work . . . . . . . . . . . . . . . . . . . . . . . . . . . . 52
  3.3 A CPN Based Framework for Agent Interactions . . . . . . . . . 55
    3.3.1 Framework Architecture . . . . . . . . . . . . . . . . . . . 56
    3.3.2 Using CPN Models to Represent Interaction Protocols . . . 58
    3.3.3 Communication Interface between Protocols and Agents . 62
4 Coloured Petri Net Based Interaction Analysis

4.1 Related Work

4.2 Analysis Techniques of PNs and CPNs
4.2.1 PN Analysis
4.2.2 CPN Analysis

4.3 A CPN Based Approach for Flexible Interaction Formation
4.3.1 Inclusion of Two Kinds of Interactions in the Approach
4.3.2 \textit{Call} and \textit{Receive} Interaction Proposals in Default Interactions
4.3.3 Protocol Analysis
4.3.4 Advantages of the Protocol Analysis

4.4 Potential Application

4.5 Summary

5 Flexible Team Formation in Self-Interested Multi-Agent Systems

5.1 System Architecture and Problem Definition
5.1.1 The System Architecture
5.1.2 Definitions and Assumptions

5.2 One-Shot and Long-Term Team Formation
5.2.1 One-Shot Teams ........................................... 134
5.2.2 Long-Term Teams ................................. 136
5.2.3 Advantages and Disadvantages of Long-term and One-shot Team Formation ......................... 137
5.3 Flexible Team Formation Mechanism ................. 138
5.3.1 Team Member Performance Evaluations ................ 138
5.3.2 System Agent Resource Evaluations ................ 140
5.3.3 Flexible Member Selection by Using Fuzzy Rules .... 140
5.4 Experiments .................................................. 146
5.5 Related Work ................................................ 149
5.6 Summary ...................................................... 150

6 An Ontology-Based Mechanism for Agent Coordination through Knowledge Management 152
6.1 Related Work ................................................. 154
6.2 Formal Expressions of Ontologies ...................... 156
6.3 Classification of MAS Ontologies ..................... 157
6.3.1 Common Ontologies of MASs ....................... 159
6.3.2 Special Ontologies of Agents ................. 161
6.4 An Ontology Based Framework for MAS Knowledge Management 163
6.4.1 Framework Structure .......................... 164
6.4.2 Knowledge Management Services ............. 165
6.5 Summary ...................................................... 171

7 Conclusions 172
7.1 Summary of Major Contributions ..................... 172
7.2 Future Works ............................................. 175

A Glossary of Terms 176
# List of Tables

<table>
<thead>
<tr>
<th>Table Number</th>
<th>Table Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Multi-agent Systems vs Centralised Systems</td>
<td>7</td>
</tr>
<tr>
<td>2.1</td>
<td>Comparison of Objective and Subjective Coordination</td>
<td>20</td>
</tr>
<tr>
<td>2.2</td>
<td>Comparison of Communication Techniques</td>
<td>27</td>
</tr>
<tr>
<td>3.1</td>
<td>Description and Comparison of CPN Development Tools</td>
<td>53</td>
</tr>
<tr>
<td>3.2</td>
<td>The Message Colour Set</td>
<td>59</td>
</tr>
<tr>
<td>3.3</td>
<td>Formal Description for the CPN Model of FIPA Inform</td>
<td>62</td>
</tr>
<tr>
<td>3.4</td>
<td>The PRO Colour Set</td>
<td>67</td>
</tr>
<tr>
<td>3.5</td>
<td>Parameter Meanings of the PRO Colour Set</td>
<td>68</td>
</tr>
<tr>
<td>3.6</td>
<td>CPN Negotiation Protocol Formal Description</td>
<td>72</td>
</tr>
<tr>
<td>4.1</td>
<td>Formal Description for CPN M</td>
<td>109</td>
</tr>
<tr>
<td>4.2</td>
<td>Forward and Backward Incidence Matrices of CPN M</td>
<td>109</td>
</tr>
<tr>
<td>4.3</td>
<td>The IntPro Colour Set</td>
<td>114</td>
</tr>
<tr>
<td>4.4</td>
<td>Forward and Backward Incidence Matrices of PP</td>
<td>122</td>
</tr>
<tr>
<td>5.1</td>
<td>Status of An Agent</td>
<td>133</td>
</tr>
<tr>
<td>5.2</td>
<td>Features of One-Shot Teams and Long-Term Teams</td>
<td>137</td>
</tr>
<tr>
<td>5.3</td>
<td>Fuzzy Rule Base Matrix</td>
<td>146</td>
</tr>
<tr>
<td>6.1</td>
<td>Formal Expression of Printer Product Ontology</td>
<td>158</td>
</tr>
<tr>
<td>6.2</td>
<td>Formal Expression of IT Product Ontology</td>
<td>162</td>
</tr>
<tr>
<td>6.3</td>
<td>Formal Expression of A Knowledge Source Ontology</td>
<td>164</td>
</tr>
</tbody>
</table>
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Intelligent Agent</td>
<td>4</td>
</tr>
<tr>
<td>1.2</td>
<td>Cooperative Degree</td>
<td>10</td>
</tr>
<tr>
<td>2.1</td>
<td>Example of a KQML Message</td>
<td>22</td>
</tr>
<tr>
<td>2.2</td>
<td>FIPA Agent Reference Model</td>
<td>25</td>
</tr>
<tr>
<td>2.3</td>
<td>The Ontolingua Server</td>
<td>31</td>
</tr>
<tr>
<td>2.4</td>
<td>The UML Model for the Contract Net Protocol</td>
<td>34</td>
</tr>
<tr>
<td>2.5</td>
<td>Organisations in a Multi-agent System</td>
<td>37</td>
</tr>
<tr>
<td>2.6</td>
<td>The Blackboard Architecture</td>
<td>38</td>
</tr>
<tr>
<td>3.1</td>
<td>An Example of Petri Nets</td>
<td>47</td>
</tr>
<tr>
<td>3.2</td>
<td>Change of Marking after Transition is Fired</td>
<td>49</td>
</tr>
<tr>
<td>3.3</td>
<td>An Example of Coloured Petri Nets</td>
<td>51</td>
</tr>
<tr>
<td>3.4</td>
<td>An Example of XML-Based CPN Format</td>
<td>52</td>
</tr>
<tr>
<td>3.5</td>
<td>CPN Based Framework for Agent Interactions</td>
<td>56</td>
</tr>
<tr>
<td>3.6</td>
<td>A CPN Place in Interaction Model</td>
<td>59</td>
</tr>
<tr>
<td>3.7</td>
<td>A CPN Transitions in Interaction Models</td>
<td>60</td>
</tr>
<tr>
<td>3.8</td>
<td>UML Model for FIPA Inform Protocol</td>
<td>61</td>
</tr>
<tr>
<td>3.9</td>
<td>CPN Model for FIPA Inform Protocol (Ready to Inform)</td>
<td>63</td>
</tr>
<tr>
<td>3.10</td>
<td>CPN Model for FIPA Inform Protocol (Informed)</td>
<td>63</td>
</tr>
<tr>
<td>3.11</td>
<td>CPN Model for FIPA Inform Protocol (Processed)</td>
<td>63</td>
</tr>
<tr>
<td>3.12</td>
<td>Structure of Comms/CPN</td>
<td>64</td>
</tr>
</tbody>
</table>
3.13 Java/CPN Interface ........................................ 65
3.14 CPN Model for Individual Agents ........................ 69
3.15 CPN Model for One-to-One Negotiation ................. 70
3.16 CPN Model for Many to Many Negotiation .......... 71
3.17 The CPN Model for Rubinstein’s Negotiation Protocol . 74
3.18 Layered Architecture ....................................... 76
3.19 The Start Transition ....................................... 77
3.20 The Consider&Modify Transition ......................... 78
3.21 One-to-One Negotiation: the seller and the buyer place Proposal Tokens to Proposal Places .......... 81
3.22 One-to-One Negotiation: the seller sends Proposal Token to buyer ................................. 82
3.23 One-to-One Negotiation: the buyer considers and modifies the received proposal ......................... 83
3.24 One-to-One Negotiation: the buyer sends modified Proposal Token to the seller ......................... 84
3.25 One-to-One Negotiation: the seller considers and modifies the proposal of the buyer ......................... 85
3.26 One-to-One Negotiation: the seller agrees on the proposal of the buyer ........................................ 86
3.27 One-to-One Negotiation: the negotiation meets a deal ........................................ 87
3.28 One-to-One Negotiation: the Proposal Token of buyer is removed by the Remove Dealt Transition, the negotiation is accomplished successfully ................................. 88
3.29 One-to-One Negotiation: no agreement is met before the deadline, i.e. the negotiation fails ................................. 89
3.30 One-to-One Negotiation Process: the negotiation terminates unsuccessfully ................................. 90
3.31 One-to-Two Negotiation: the seller and buyers place their Proposal Tokens in Proposal Places .......... 93
3.32 One-to-Two Negotiation: the seller sends its Proposal Tokens . . . 94
3.33 One-to-Two Negotiation: buyers modify proposals according to
the received proposal from the seller . . . . . . . . . . . . . . . . . . 95
3.34 One-to-Two Negotiation: negotiations terminates successfully/unsuccessfully 96

4.1 Petri Net N . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 104
4.2 Firing of \( t_1 \) in \( N \) . . . . . . . . . . . . . . . . . . . . . 107
4.3 A Coloured Petri Net \( M \) . . . . . . . . . . . . . . . . . . . . . 108
4.4 The Framework for Flexible Interactions . . . . . . . . . . . . . . . 111
4.5 Call and Receive Interaction Proposals . . . . . . . . . . . . . . . 113
4.6 An Example of a Protocol Proposal . . . . . . . . . . . . . . . . . 115
4.7 The Specification of a Proposed Protocol . . . . . . . . . . . . . . . 116
4.8 Place Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 119
4.9 To Reject a Proposed Protocol in Place Type Analysis . . . . . . . . 120
4.10 Use CPN Model to Represent a SR Relation . . . . . . . . . . . . . 126

5.1 The System Architecture . . . . . . . . . . . . . . . . . . . . . . . 132
5.2 Fuzzy Membership Function for \( ur/cr \) . . . . . . . . . . . . . . 142
5.3 Fuzzy Membership Function for \( ara \) . . . . . . . . . . . . . . . 143
5.4 Fuzzy Membership Function for \( ct/el \) . . . . . . . . . . . . . . . 145
5.5 Agent Searching Time Comparison . . . . . . . . . . . . . . . . . . 147
5.6 Award Distribution Situation Comparison . . . . . . . . . . . . . . 148

6.1 Ontology of IT Product . . . . . . . . . . . . . . . . . . . . . . . . 161
6.2 Knowledge Source Ontology . . . . . . . . . . . . . . . . . . . . . 163
6.3 The Framework for MAS Knowledge Management . . . . . . . . . . 166
6.4 The Knowledge Source Registry Service . . . . . . . . . . . . . . . 168
6.5 Knowledge Monitor and Refreshing from External Knowledge Servers