

# Wireless Optimisation Based on Economic Criteria

by

Siew Lee Hew

B.E. (IT & T, HONS. 1)

Thesis submitted for the degree of

**Doctor of Philosophy**

in

School of Electrical and Electronic Engineering,  
Faculty of Engineering, Computer and Mathematical Sciences

The University of Adelaide, Australia

2006

© Copyright 2006  
Siew Lee Hew  
All Rights Reserved



Typeset in L<sup>A</sup>T<sub>E</sub>X 2<sub>ε</sub>  
Siew Lee Hew

# Statement of Originality

This work contains no material that 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 the thesis, when deposited in the University Library, being available for loan and photocopying.

---

Signed

---

Date

# Acknowledgements

I am highly indebted to my principal supervisor Professor Langford B. White for his guidance, support, motivation and encouragement throughout my candidature. Working with such an inspiring and excellent mentor has been an insightful journey for me. I still have a lot to learn from him, who never ceases to explore new knowledge.

I have profited immensely from various discussions with my two other excellent supervisors, Dr. Paul Chapman and Dr. Matthew Sorell. Particularly, my simulation work on Smart Pricing with them at the beginning of this research has sparked the idea for our work in Chapter 3. I am also grateful to them for patiently helping me to improve my writing skills.

This research would not have been possible without the generous financial help in the form of the Australian Postgraduate Award (APA) and the CRC for Smart Internet Technology top-up scholarships. I would also like to thank the CRC for Smart Internet, University of Adelaide, and ACORN for sponsoring my workshop and conference travels.

My sincere gratitude also goes to my wonderful colleagues at the Centre for Internet Research (CIR) who have given me a friendly second home for the past three years. Extra kudos to those (especially Ange) who gave me chocolates and lollies from time to time! I am also thankful to the friendly people working at the main office of the School of Electrical and Electronic Engineering for their help regarding various matters.

Last but not least, I would like to thank my partner and family. Without your encouragement, emotional support and understanding, I will never be able to complete this remarkable but often challenging journey.

*Siew-Lee Hew*

April 2006

# Abstract

The rapid growth in demand due to the emergence of mobile communication services with variable rates, coupled with the resource scarcity of mobile air interface, has encouraged researchers to find technological solutions to increase spectral efficiency in order to support different levels of Quality of Service (QoS). Radio resource management (RRM) plays a major role in QoS provisioning and congestion control for wireless networks. The main problem with the congestion control mechanisms provided by current RRM schemes is that they are mostly reactive, triggered only when congestion occurs. The common, traditional solution to congestion has been for system planners to *over-engineer* a network by assigning more resources than are necessary. This approach is very costly because busy periods are usually brief, causing the network to be often under-utilised outside of these periods. Current static, usage-based pricing models also fail to assist in traffic shaping to even out loads.

Economic modelling offers a new perspective into current RRM schemes and enables efficient utilisation of scarce resources and congestion prevention based on concepts such as utility, price, Pareto optimality and game theory. Dynamic pricing has been proposed as a mechanism to encourage users to adapt their resource consumption level according to network conditions. A good pricing model can provide the necessary positive incentives to increase users' arrival rate when the network load is relatively low and negative incentives for users to defer their usage when the load is relatively high. In this dissertation, we propose an economic framework for pricing and RRM for 3G and beyond systems. Our aim is two-fold: to calculate an optimal integrated dynamic pricing and RRM policy; and to allocate scarce network resources in a fair and Pareto-optimal manner.

The optimal integrated dynamic pricing and RRM policy is computed based on the stochastic distribution of users' budget, arrivals, handoffs and departures. Our results

show that the integrated policy is superior in terms of average reward improvement and congestion prevention to current schemes that use static pricing models. In interference-based networks such as WCDMA, we suggest users be charged according to their noise rise factor, i.e. an estimate of the amount of interference generated by the call. This interference-based pricing model improves on the conventional load-based model in by delivering higher revenue and lower call blocking and handoff probabilities.

Using the axiomatic bargaining concepts from cooperative game theory, we derive a class of fair and Pareto-optimal bargaining solutions that allocate wireless resources based on users' minimum and maximum rate requirements. We propose two models: symmetric and asymmetric. In the latter, resource is allocated according to the price paid by the users. An important significance of the asymmetric bargaining model is that this solution is still Pareto-optimal and fair according to the users' bargaining power. Our approach is also a departure from current works using noncooperative game theory that can only achieve an inefficient outcome, i.e. the Nash equilibrium; or cooperative game theory that focus on only one solution on the Pareto-optimal boundary. By analysing a range of bargaining solutions instead of specific ones, operators can proceed to select the best outcome out of these Pareto-optimal solutions based on criteria like revenue.

# Publications

1. S-L. Hew and L. B. White, “Interference-based dynamic pricing and radio resource management for WCDMA networks”, in *Proc. of 61st IEEE Vehicular Technology Conference (VTC2005-Spring)*, May 30 - June 1 2005, Stockholm, Sweden.
2. S-L. Hew and L. B. White, “Optimal integrated call admission control and dynamic pricing with handoffs and price-affected arrivals”, in *Proc. of Asia-Pacific Conference on Communications (APCC’05)*, Oct. 3-5 2005, Perth, Australia.
3. S-L. Hew and L. B. White, “Fair resource bargaining solutions for cooperative multi-operator networks”, in *Proc. of IEEE International Zurich Seminar on Communications (IZS’06)*, Feb. 22-24 2006, Zurich, Switzerland.
4. S-L. Hew and L. B. White, “A game theoretical approach for resource bargaining in shared WCDMA networks: symmetric and asymmetric models”, in *Proc. of 1st IEEE International Conference on Wireless Broadband and Ultra Wideband Communications (AusWireless’06)*, Mar. 13-16 2006, Sydney, Australia.
5. S-L. Hew and L. B. White, “Integrated call admission control and dynamic pricing in multiservice networks with price-affected arrivals, retrials and substitutions”, submitted for publication.
6. S-L. Hew and L. B. White, “Interference-based dynamic pricing for WCDMA networks using neuro-dynamic programming”, accepted for publication in *IEEE Trans. on Automatic Control*.
7. S-L. Hew and L. B. White, “Cooperative resource allocation games in shared networks”, submitted to *IEEE Trans. on Wireless Communications*, in Feb. 2006.

# Dedication

This dissertation is dedicated to my parents, *Hew Peng Fah* and *Tan Hong Gaik*, for their sacrifice, valuable teachings and unconditional support all these years.



# Contents

Statement of Originality	iii
Acknowledgements	v
Abstract	vii
Publications	ix
Dedication	xi
Contents	xiii
List of Figures	xix
List of Tables	xxiii
<b>Chapter 1. Introduction</b>	<b>1</b>
1.1 Background and Motivation . . . . .	3
1.1.1 Radio Resource Management . . . . .	3
1.1.2 Economic Modelling . . . . .	7
1.1.3 Pricing and Charging Models in Communication Networks . . . . .	9
1.2 An Economic Framework for Pricing and RRM . . . . .	12

## Contents

---

1.3	Organisation and Original Contributions . . . . .	14
1.3.1	Chapter 2: Background . . . . .	14
1.3.2	Chapter 3: Integrated Call Admission Control and Dynamic Pricing Cellular Networks . . . . .	14
1.3.3	Chapter 4: Interference-based Radio Resource Management and Dynamic Pricing for WCDMA Networks . . . . .	15
1.3.4	Chapter 5: Cooperative Resource Bargaining Games for Shared Networks . . . . .	17
1.3.5	Chapter 6: Conclusion . . . . .	18
<b>Chapter 2. Background</b>		<b>19</b>
2.1	WCDMA System . . . . .	19
2.1.1	Wireless Resource Parameters . . . . .	20
2.2	Economic Modelling Concepts . . . . .	23
2.2.1	Game Theory . . . . .	23
2.2.2	Pricing Schemes for Wired Networks . . . . .	29
2.2.3	Pricing Schemes for Wireless Networks . . . . .	34
2.3	Optimal Control Theory . . . . .	39
2.3.1	Dynamic Programming . . . . .	39
2.3.2	Neuro-Dynamic Programming . . . . .	41
<b>Chapter 3. Integrated Dynamic Pricing and Call Admission Control</b>		<b>43</b>
3.1	Introduction . . . . .	43
3.2	System Model . . . . .	46
3.3	Markov Decision Problem Formulation . . . . .	49
3.3.1	State Space and Transition Rates . . . . .	49

3.3.2	Event and Control Space . . . . .	51
3.3.3	Revenue Maximisation Problem . . . . .	52
3.4	Calculation of Stationary Probabilities . . . . .	57
3.4.1	Level-Dependent Quasi-Birth-Death Process . . . . .	58
3.4.2	Matrix Analytic Methods . . . . .	58
3.4.3	System Characteristics . . . . .	59
3.5	Numerical Results . . . . .	61
3.5.1	Policy Comparison . . . . .	63
3.5.2	Congestion Control . . . . .	67
3.5.3	Price Discrimination . . . . .	70
3.5.4	Exponential WTP Distribution . . . . .	71
3.6	Conclusions . . . . .	72
 <b>Chapter 4. Interference-based Dynamic Pricing and RRM</b>		 <b>75</b>
4.1	Introduction . . . . .	75
4.2	System Model . . . . .	77
4.2.1	Load-based Pricing . . . . .	78
4.2.2	Interference-based Pricing . . . . .	79
4.3	Dynamic Programming Formulation . . . . .	82
4.4	Neuro-Dynamic Programming Formulation . . . . .	84
4.4.1	Approximation Architecture . . . . .	85
4.4.2	TD(0) Learning Algorithm . . . . .	87
4.4.3	Exploitation and Exploration . . . . .	88
4.5	Numerical Results . . . . .	89
4.5.1	Normal Traffic Load . . . . .	92

## Contents

---

4.5.2	Heavy Traffic Load . . . . .	94
4.5.3	Effects of Exploration . . . . .	96
4.5.4	Effects of a Price Sliding Window . . . . .	97
4.6	Conclusions . . . . .	98

## Chapter 5. Cooperative Resource Allocation Games in Shared Networks 101

5.1	Introduction . . . . .	101
5.2	Network Sharing Models . . . . .	105
5.3	System Model . . . . .	106
5.3.1	Uplink Load Factor . . . . .	107
5.3.2	Downlink Load Factor . . . . .	108
5.4	Cooperative Game Theory Framework . . . . .	109
5.5	Resource Bargaining in WCDMA . . . . .	112
5.5.1	Symmetric Bargaining . . . . .	112
5.5.2	Asymmetric Bargaining . . . . .	114
5.5.3	Revenue Optimisation . . . . .	117
5.6	Resource Sharing Among Competing Operators . . . . .	118
5.7	Numerical Analysis and Discussions . . . . .	120
5.8	Conclusion . . . . .	123

## Chapter 6. Conclusion 125

6.1	Summary . . . . .	125
6.2	Potential Directions for Further Research . . . . .	128
6.2.1	Online Dynamic Pricing Schemes . . . . .	128
6.2.2	Stochastic Pricing and Resource Allocation Games . . . . .	129

6.2.3 Noncooperative Implementation of the Cooperative Bargaining Solutions in Self-organising Networks . . . . .	130
<b>Appendix A. Appendix</b>	<b>133</b>
A.1 Infinitesimal Generator . . . . .	133
<b>Bibliography</b>	<b>135</b>

# List of Figures

1.1	A typical hourly arrival pattern in a mobile network. . . . .	2
1.2	Radio Resource Management model consists of call admission control, rate control and power control. . . . .	4
1.3	An Economic Framework for Pricing and Radio Resource Management. . .	13
2.1	The Nash, Raiffa-Kalai-Smorodinsky and utilitarian bargaining solutions are special instances on the Pareto-optimal boundary. They can be obtained by varying the value of $\beta$ in the preference function. . . . .	27
3.1	Integrated call admission control and dynamic pricing model. . . . .	44
3.2	The probability distribution function of WTP using variable shapes $\beta$ . . .	46
3.3	Transition Diagram of state $s = (\mathbf{x}, \mathbf{n})$ . . . . .	50
3.4	WTP pdfs and access probabilities vs. price with $\beta = 3.5$ and $1.0$ . . . . .	62
3.5	Optimal revenue per stage $J^*$ for WTP shape $\beta = 3.5$ . . . . .	63
3.6	Optimal call admission policy of OCADP. The x and y axes indicate the state of service 1, $s_1 = (n_1, x_1)$ , and 2, $s_2 = (n_2, x_2)$ , respectively. The combination of $s_1$ and $s_2$ forms a state $s = (s_1, s_2)$ in the system. The CAC policy of each state is indicated by the following symbols: 'o' represents $\mathbf{u}_c = (0, 1)$ and ' $\otimes$ ' represents $\mathbf{u}_c = (0, 0)$ . States with ' $\square$ ' are states where the bandwidth of the system is fully utilised. In other states, $\mathbf{u}_c = (1, 1)$ . . .	64
3.7	Optimal differential reward rate, $h^*(s)$ . . . . .	65

## List of Figures

---

3.8	Optimal prices per bandwidth time for OCADP with $B = 20$ , $\psi = (1, 1)$ per bandwidth time and $\mathbf{b} = (2, 2)$ . The x and y axes indicate the state of service 1, i.e. $s_1 = (n_1, x_1)$ , and 2, i.e. $s_2 = (n_2, x_2)$ respectively. The combination of $s_1$ and $s_2$ forms a state. . . . .	66
3.9	Stationary probabilities of a system with $B = 20$ and $\mathbf{b} = (2, 2)$ . The x and y axes indicate that the state of service 1, $s_1 = (n_1, x_1)$ , and 2, $s_2 = (n_2, x_2)$ , respectively. The intersection of $s_1$ and $s_2$ forms a state $s \in \mathcal{S}$ . OCADP controls network congestion by shifting stationary probabilities from states with high number of busy connections to less busy states. . . . .	68
3.10	Stationary probabilities of a system with $B = 20$ and $\mathbf{b} = (2, 2)$ . OCADP controls network congestion by shifting stationary probabilities from states with high number of busy connections to less busy states. . . . .	69
3.11	Optimal reward per stage $J^*$ under OCADP (with and without price discrimination). . . . .	71
3.12	Optimal reward per stage $J^*$ for WTP shape $\beta = 1.0$ . . . . .	72
4.1	The interference level in the network, indicated by the system noise rise, rises exponentially as the system load factor increases. . . . .	80
4.2	The noise rise factor, i.e. the interference generated by a call, increases exponentially as the system load factor increases although the individual load factor remains the same throughout. . . . .	80
4.3	(a) A general feature-based approximation architecture. (b) An approximation architecture with feature vector $\boldsymbol{\theta}_k$ and future reward rate. . . . .	85
4.4	Average reward per time, $\tilde{J}_k$ , and parameter vector, $\boldsymbol{\theta}_k$ , averaged for every 250 steps, under O-NRF. . . . .	91
4.5	Average reward and proportion of reward obtained under normal load. . . . .	92
4.6	The relationship between ILF/NRF and System Load Factor . . . . .	93
4.7	Blocking, dropping and access probabilities under normal load. . . . .	94
4.8	Average load factor and noise rise under normal load. . . . .	95

4.9	Average reward and proportion of reward obtained under heavy traffic load.	95
4.10	Average load factor and noise rise under heavy traffic load. . . . .	96
4.11	Average reward and proportion of reward obtained under policies O-ILF and O-NRF with 20% to 80% state exploration. . . . .	97
4.12	Results under heavy traffic load using a price sliding window. . . . .	99
5.1	Resource allocation games in a shared network. . . . .	103
5.2	Models of network sharing. . . . .	105
5.3	Geometrical interpretation of the symmetric and asymmetric Nash and Raiffa solutions. . . . .	121
5.4	Symmetric and asymmetric bargaining solutions with $\hat{\tau} = (0.5, 0.5)$ and $\hat{\tau} = (0.70, 0.30)$ respectively. . . . .	122
5.5	Operator's revenue using $\beta = 0, 1$ for varying bargaining powers. . . . .	122
6.1	Summary of the contributions of this dissertation and key distinctions with existing works. . . . .	126
6.2	Modified feature-based approximation architecture with parameter estimation. . . . .	129



# List of Tables

2.1	Summary of the use of pricing in wireless networks. . . . .	36
3.1	System parameters derived using stationary distribution of the system. . .	60
3.2	Simulation parameters for AASP, OCASP, AADP and OCADP policies. . .	62
4.1	Simulation parameters for S-ILF, S-NRF, O-ILF and O-NRF policies. . . .	90