Signal Processing for Distributed Nodes in Smart Networks

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Except where otherwise indicated, this thesis is my own original work.

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Preface

This thesis has been submitted to the College of Engineering and Computer Science of The Australian National University (ANU) in fulfillment of the requirement for the degree of Doctor of Philosophy (Ph.D.). The studies were carried out over a period of three years and eight months, from April 2009 to December 2012. The research was funded by National ICT Australia (NICTA) through NICTA tuition fee scholarship, NICTA Ph.D. scholarship, NICTA Ph.D. supplementary scholarship, and NICTA Ph.D. assignment scholarship. My supervisors have been Dr. David B. Smith, Dr. Jian A. Zhang, Dr. Tharaka A. Lamahewa, and Dr. Thushara D. Abhayapala.

Dedication

This thesis is dedicated to my mother Mrs. Shahana Ferdous.

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Wayes Tushar

Abstract

With increasing environmental concern for energy conservation and mitigating climate change, next generation smart networks are bound to provide improved performance in terms of security, reliability, and energy efficiency. For instance, future smart networks will work in highly complex and dynamic environments and will have distributed nodes that need to interact with each other and may also interact with an energy provider in order to improve their performance. In this context, advanced signal processing tools such as game theory and distributed transmit beamforming can yield tremendous performance gains in terms of energy efficiency for demand management and signal transmission in smart networks.

The central theme of this dissertation is the modeling of *energy usage behavior* of *self-seeking* distributed nodes in smart networks. The thesis mainly looks into two key areas of smart networks: 1) smart grid networks and 2) wireless sensor networks, and contains: an analytical framework of the economics of electric vehicle charging in smart grids in an energy constrained environment; a study of a consumer-centric energy management scheme for encouraging the consumers in a smart grid to voluntarily take part in energy management; an outage management scheme for *efficiently* curtailing energy from the consumers in smart grids in the event of a power outage; a comprehensive study of power control of sensors in a wireless sensor network using game theory and distributed transmit beamforming; and finally, an energy aware distributed transmit beamfoming technique for long distance signal transmission in a wireless sensor network.

This thesis addresses the challenges of modeling the energy usage behavior of distributed nodes through studying the propriety of energy users in smart networks, 1) by capturing the interactions between the energy users and energy provider in smart grids using non-cooperative Stackelberg and generalized Nash games, and showing that the socially optimal energy management for users can be achieved at the solution of the games, and 2) by studying the power control of sensors in wireless sensor networks, using a non-cooperative Nash game and distributed transmit beamforming that demonstrates significant transmit energy savings for the sensors. To foster energy efficient transmission, the thesis also studies a distributed transmit beamforming technique that does not require any channel state information for long distance signal transmission in sensor networks.

The contributions of this dissertation are enhanced by proposing suitable system models and appropriate signal processing techniques. These models and techniques can capture the different cost-benefit tradeoffs that exist in these networks. All the proposed schemes in this dissertation are shown to have significant performance improvement when compared with existing solutions. The work in this thesis demonstrates that modeling power usage behavior of distributed nodes in smart networks is both possible and beneficial for increasing the energy efficiency of these networks.

List of Publications

Much of the work in this thesis has been published or has been submitted for publication in refereeed journals and conference proceedings. The following is a list of publications (Tushar2012a–Tushar2010).

[Tushar2012a] W. Tushar, J. A. Zhang, S. Thiebaux, D. B. Smith and H. V. Poor,"A Consumer-Centric Energy Management Scheme for Smart Grid," under consideration to appear in *IEEE Transactions on Smart Grid*, 2013.

[Tushar2012b] W. Tushar, J. A. Zhang, D. B. Smith, S. Thiebaux, and H. V. Poor,"Prioritizing Consumers in Smart Grid: Energy Management Using Game Theory," in *Proc. of the IEEE International Conference on Communications* (ICC), Budapest, Hungary, 2013, pp. 1–5.

[Tushar2012c] W. Tushar, W. Saad, H. V. Poor and D. B. Smith,"Economics of Electric Vehicle Charging: A Game Theoretic Approach," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1767-1778, Dec., 2012.

[Tushar2012d] W. Tushar, J. A. Zhang, D. B. Smith, H. V. Poor, G. Platt and S. Durrani,"An Efficient Energy Curtailment Scheme for Outage Management in Smart Grid," in *Proc. of the IEEE Global Communications Conference* (GLOBECOM), Los Angeles, USA, Dec., 2012, pp. 1-6.

[Tushar2012e] W. Tushar, D. B. Smith and T. A. Lamahewa, "Distributed Transmit Beamforming: Data Funneling in Wireless Sensor Network," in *Proc. of the Australian Communications Theory Workshop* (AusCTW), Wellington, New Zealand, Jan., 2012, pp. 1-6.

[Tushar2012f] W. Tushar, D. B. Smith, T. A. Lamahewa and J. A. Zhang,"Non-cooperative Power Control Game in a Multi-Source Wireless Sensor Network," in *Proc. of the Australian Communications Theory Workshop* (AusCTW), Wellington, New Zealand, Jan., 2012, pp. 1-6. (**Best paper award**)

[Tushar2012g] W. Tushar, D. B. Smith, J. A. Zhang, T. A. Lamahewa and T. Abhayapala,"Distributed Transmit Beamforming: Phase Convergence Improvement Using Enhanced One-Bit Feedback" in *Proc. of the IEEE Wireless Communications and Networking Conference* (WCNC), Paris, France, Apr., 2012, pp. 1-6.

[Tushar2012h] W. Tushar, D. B. Smith, W. Saad and H. V. Poor,"Distributed Transmit Beamforming: Performance Improvement Using Two-Bit Feedback Scheme," in *Proc. of the International Symposium on Communications and Information Technologies* (ISCIT), Gold Coast, Australia, Oct., 2012, pp. 1-6.

[Tushar2010] W. Tushar and D. B. Smith,"Distributed Transmit Beamforming Based on

a 3-Bit Feedback System," in *Proc. of the IEEE International Workshop on Signal Processing Advances in Wireless Communications* (SPAWC), Marrakech, Morocco, Jun., 2010, pp. 1-5.

Contents

List of Figures

List of Tables

Glossary

Abbreviations

PEVG	Plug-in electric vehicle group.
PEV	Plug-in electric vehicle.
BEV	Battery only electric vehicle.
PHEV	Plug-in hybrid electric vehicle.
SG	Smart grid.
SEM	Smart energy manager.
MWh	Mega Watt hour.
GNEP	Generalized Nash equilibrium problem.
GNE	Generalized Nash equilibrium.
GSG	Generalized Stackelberg game.
GSE	Generalized Stackelberg equilibrium.
VE	Variational equilibrium.
VI	Variational Inequality.
KKT	Karush-Kuhn-Tucker.
S-S	Solodov and Svaiter.
V2G	Vehicle to grid.
USD	US dollar.
PSO	Particle swarm optimization.
ED	Equal distribution.
CPS	Central power station.
EC	Energy consumer.
G2V	Grid to vehicle.
FIT	Feed-in tariff.
EV	Electric vehicle.
SLMFG	Single-leader multiple-follower game.
EMES	Energy management equilibrium solution.
SSHPM	S-S hyperplane projection method.
kWh	kilo Watt hour.
ECG	Energy curtailment game.
ES	Energy source.
EU	Energy user.
LAN	Local area network.
CPP	Customer preference parameter.
VIP	Variational inequality problem.
LPM	Leading principal minor.
EEC	Equal energy curtailment.
TDMA	Time division multiple access.

SINR	Signal to interference-noise ratio.
QoS	Quality of service.
BS	Base station.
NPG	Non-cooperative power control game.
IP	Interference power.
DTB	Distributed transmit beamforming.
SEP	Symbol error probability.
CS	Cooperative sensor.
CH	Cluster head.
CM	Cluster member.
DF	Directional flood.
PSK	Phase shift keying.
i.i.d	Independently and identically distributed.
CSI	Channel state information.
ML	Maximum likelihood.
SNR	Signal to noise ratio.
RP	Receiving point.
BPSK	Binary phase shift keying.
QPSK	Quadrature phase shift keying.
RSS	Received signal strength.
BER	Bit error rate.
SON	Self organizing network.

Symbols

Some symbols used in this dissertation have different meanings in different chapters. Hence, we do not provide global definition here. All symbols will be defined in the context of each chapter in which they appear.