Adaptive Topologies - Improving Wireless Networks Through the Use of Additional Nodes and Power Control

Robert Anthony Hunjet
School of Electrical and Electronic Engineering

4th February 2014

Contents

List of Acronyms

AGCS Average Greatest Component Size

AGCS Average Greatest Component Size

BAP Bridge and Articulation Point detection

BAP-BS Bridge and Articulation Point detection with Bridge Safety

BAP-BS Bridge and Articulation Point detection with Bridge Safety

BFS Breadth First Search

BM Blocking Matrix

CA Collision Avoidance

CBTC Cone Based Topology Control

CDCIN The Centre for Defence Communications and Information Networking

CDMA Code Division Multiple Access

CEM Cross Entropy Method

CEWD Communications and Electronic Warfare Division

CSMA Carrier Sense Multiple Access

CTS Clear to Send

DFS	Depth First Search
DIDO	Distributed In Distributed Out
DSTO	Defence Science and Technology Organisation
EIRP	Effective Isotropic Radiated Power
GPS	Global Positioning System
GUC	Ground Unit Connectivity
GUC	Ground Unit Connectivity
HPPP	Homogeneous Poisson Point Process
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
LMST	Localized Minimum Spanning Tree
LTE	Long Term Evolution
LTRT	Local Tree-based Reliable Topology
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MASON	Multi Agent Simulator Of Networks
MIHAN	Minimalist Instant Handoff for wireless Access Networks
MIMO	Multiple-Input and Multiple-Output
MOCEO	Multi-Objective Cross Entropy Optimisation
MSP	Median Spaced Pairs

MSPRP	Median Spaced Pairs with Reduced Power
MST	Minimum Spanning Tree
NAV	Networked Autonomous Vehicle
NCW	Network Centric Warfare
PSO	Particle Swarm Optimisation
RTS	Request to Send
SG	Spectral Gap
SG-AP	Spectral Gap with Articulation Point Detection
SG-AP	Spectral Gap with Articulation Point Detection
SG-AP-BS	Spectral Gap with Articulation Point Detection with Bridge Safety
SG-AP-BS	Spectral Gap with Articulation Point Detection with Bridge Safety
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference Ratio
SN	Survivable Networks
SNR	Signal to Noise Ratio
SSM	Separation Score Maximisation
UANC	Uniform Average Network Capacity
UAV	Unmanned Aerial Vehicle
VDTN	Vehicular Delay Tolerant Network
WCDMA	Wideband Code Division Multiple Access
WSN	Wireless Sensor Network

List of Figures

List of Tables

Abstract

The work presented in this thesis shows that shared spectrum wireless networks can be enhanced through the use of additional nodes and power control. Network improvement is demonstrated in three key areas: connectivity, capacity and power efficiency. It is also shown that the techniques developed to increase network capacity and power efficiency have a positive effect on the security of the network. Mobile ad hoc networks are the specific focus of the work, but the results are applicable to both wireless sensor networks and shared spectrum wireless infrastructure based networks.

This thesis demonstrates how additional nodes may be used in mobile wireless networks to maintain connectivity by specifically targeting bridges and articulation points. It then takes a graph theoretical approach to networking, with the assumption that lowering interference increases network capacity, to show that additional nodes combined with power control can be used to simultaneously increase the capacity and power efficiency of wireless networks. An implementation of a novel method to generate all possible transmission states under a Request To Send (RTS) / Clear To Send (CTS) scheme is used in the creation of a repeatable metric, Uniform Average Network Capacity (UANC). This metric describes the capacity that can be held within a network, and is suitable for comparing one network to another, enabling its use in optimisations. UANC is used in a multi objective cross entropy optimisation of capacity and power efficiency to create Pareto optimal sets of viable network topologies which exhibit high capacity and low power use. The work presented then derives the conditions under which n simultaneous transmissions are beneficial to capacity. This leads to the definition of a separation multiplier, i.e., the ratio of distances between receivers and between senders and their receivers, which is used to create wireless networks which exhibit high UANC. The separation multiplier is then utilised in existing networks, where topologies are altered

through the modification of transmission powers and the use of additional nodes, to create higher capacity networks, showing that additional nodes can benefit network capacity. This technique has the added benefit of increasing network power efficiency.

A modification to the RTS/CTS protocol which uses the separation multiplier is then presented. The new scheme has the effect of allowing only beneficial simultaneous transmissions to occur. It is shown through simulation that this approach increases network capacity. Networks which implement the capacity and power efficiency enhancing measures presented are shown to exhibit increased security, in that the lowering of transmission power and allowance of multiple transmissions within the network reduces the distance at which transmissions can be detected and decoded. Finally, an implementation of the overall knowledge gained through the thesis is presented, augmenting existing networks with additional nodes and power control to create bi-connected, power efficient and high capacity networks.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution in my name 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. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint - award of this degree. 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. The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works. I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Robert Hunjet

Acknowledgements

I would like to take this opportunity to express my thanks to Dr Matthew Sorell, Electrical and Electronic Engineering, The University of Adelaide for his supervision and advice. My thanks also goes to Dr Andrew Coyle of The Centre for Defence Communications and Information Networking (CDCIN), The University of Adelaide, for his guidance and supervision associated with this work.

I would like to thank my workplace, the Defence Science and Technology Organisation (DSTO), specifically Assured Communications Branch under the guidance of Dr Peter Shoubridge, Communications and Electronic Warfare Division (CEWD), for giving me the opportunity to undertake this research. My sincere thanks is expressed to Dr Marek Kwiatkowski, Head of Survivable Networks Group (SN), CEWD, DSTO, for his support and the belief expressed in me in regards to this work.

My appreciation is also expressed to Dr Michael Webb, CDCIN, The University of Adelaide, and Dr Peyam Pourbeik, SN, CEWD, DSTO, for their comments and feedback on a former manuscript of this thesis.

Finally, I would like to thank my wife, Linda, for her support and editorial guidance in the publications associated with this thesis, and my daughter, Evie, who provides me with new inspiration on a daily basis.

For Evie

Foreword

This thesis is primarily concerned with examining whether the use of additional nodes combined with transmission power control of all nodes in the network can improve a mobile ad hoc network's performance. A well known result in the literature is that of Gupta and Kumar [35] which shows that increasing the number of nodes in a wireless network reduces the capacity available to each node. This result is derived under certain assumptions. This thesis shows that if these assumptions are relaxed and the node addition is combined with suitable power control measures, then additional nodes can, in fact, increase wireless network capacity whilst simultaneously increasing survivability, power efficiency and, as a result, security.

The layout of this thesis is as follows:

- Chapter 1 introduces the problem and the individual areas of research being addressed. It then provides a summary of the contributions made by this thesis.

- Chapter 2 provides essential background information on the fields of research relevant to this body of work.

- Chapter 3 explains how the use of additional nodes can improve the connectivity of wireless networks by specifically targeting weak points within the networks.

- Chapter 4 defines the capacity and power efficiency problem from a graph theoretical perspective. It shows that the state space associated with placing an additional node within a network to reduce the interference is extremely undulating and, as such, hill climbing optimisation approaches are not appropriate.

- Chapter 5 builds on the knowledge gained from Chapter 4 and uses a population based optimisation approach to show that the addition of nodes to a network can improve its power efficiency and capacity from a graph theoretical perspective.

- Chapter 6 moves away from a graph theoretical approach and introduces a new method for generating the valid transmission states of a network subject to the carrier sense multiple access / collision avoidance CSMA/CA (RTS/CTS) protocol. It then uses these states to create a new measure for network capacity, Uniform Average Network Capacity (UANC). Networks are optimised for power efficiency, then UANC. A novel use of a multi-objective cross entropy optimisation is then presented which seeks to simultaneously increase power efficiency and UANC. It is shown that a multi-objective approach produces superior networks, the gains of which can be enhanced further through the appropriate placement of additional nodes.

- Chapter 7 investigates increasing the capacity of a wireless network analytically. The conditions under which simultaneous transmissions are of benefit to network capacity are derived and it is shown that relaying is not necessarily a hindrance to capacity. The work is verified through simulation where high capacity networks are built through implementation of the required conditions, and it is shown that, with the use of additional nodes, existing networks can be augmented to closely match the conditions required and have their capacity increased. The graph theoretical, optimisation based and analytical results are compared to determine the appropriate network conditions for the suggested algorithms.

- Chapter 8 suggests a modification to the RTS/CTS protocol to help realise the capacity increasing conditions derived in Chapter 7. It is verified through simulation that these modifications can increase wireless network capacity and that these gains can be enhanced through the use of additional nodes.

- Chapter 9 discusses the security benefits gained when networks adhere to the findings of the previous chapters.

- Chapter 10 shows how the knowledge gained from the previous chapters can be amalgamated to create robust networks providing high capacity and power efficiency.

- Chapter 11 presents concluding remarks and highlights potential future work stemming from the research presented in this thesis.

Associated Publications

The majority of the work presented in this thesis has been published or submitted for publication. The papers associated with the work have been referenced in the appropriate chapters. Although some of the referenced papers have been co-authored, they were created from the work I have undertaken in preparation of this thesis. In all cases, I was the primary author, created the methods presented and performed the work. The co-authors provided some suggestions to the work and assistance in editing the manuscripts.

1. R. Hunjet and A. Coyle. *Increasing Capacity in Wireless Networks at the Physical and Link Layers.* To be submitted, 2014.

2. R. Hunjet and Ping Hui. *Maintaining Connectivity in Mobile Adhoc Networks Using Distributed Optimisation.* In Communications and Information Systems Conference (MilCIS), 2011 Military, pages 1-6, 2011.

3. R. A. Hunjet. *Power and Placement: Increasing Mobile Adhoc Network Capacity and Power Efficiency.* In Telecommunication Networks and Applications Conference, 2008. ATNAC 2008. Australasian, pages 198-203.

4. R. A. Hunjet, A. Coyle, and M. Sorell. *Enhancing Mobile Adhoc Networks Through Node Placement and Topology Control.* In Wireless Communication Systems (ISWCS), 2010 7th International Symposium on, pages 536-540.

5. Robert Hunjet. *A Capacity Enhancing Modification to RTS/CTS.* To be Submitted, 2014.

6. Robert Hunjet. *Towards Better Wireless Networks.* To be submitted, 2014.

7. Robert Hunjet and Andrew Coyle. *On Optimising the Capacity and Power Efficiency of a Wireless Network.* In Telecommunication Networks and Applications Conference (ATNAC), 2012 Australasian, pages 1-7.