UNIVERSITI PUTRA MALAYSIA

ENERGY-EFFICIENT MEDIUM ACCESS CONTROL STRATEGY FOR COOPERATIVE WIRELESS NETWORKS

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By

MAHMOUD SAMI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

August 2016

DEDICATION

I dedicate this thesis to
My Parents
and
My wife
because of all their supports, encouragements and love.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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August 2016

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Green communication has recently gained much attention, as it not only guarantees Quality of Service (QoS) and minimizes cost and energy consumption, but it is also environmentally benign. The paradigm shift toward energy-efficient communication has newly intensified in various technical approaches. Cooperative communication has been introduced as an effective, energy-efficient transmission technique, in which the single antenna nodes are encouraged to share their resources and construct a virtual Multi Input Multi Output (MIMO) system, resulting in higher diversity gain and throughput. Cooperative communication is considered as an efficient solution for mobile nodes where some difficulties in terms of physical size and energy consumption arise from implanting multiple antennas. However, the benefits of cooperative communication would be degraded by traditional, higher layer protocols designed for legacy non-cooperative systems. Thus, considering the impact of cooperation on higher layers and designing a MAC protocol are essential.
This study introduces a new cooperative MAC protocol called EAP-CMAC (Energy Aware Physical-layer Network Coding Cooperative MAC) that integrates cooperative communication into PNC in wireless ad-hoc networks. In EAP-CMAC, the best transmission mode is selected among direct transmission, traditional cooperation and PNC-based transmission by considering the destination queue and source-destination link quality.

Moreover, a joint relay selection and power allocation algorithm is proposed based on location information and the nodes residual energy that significantly improves the network lifetime and energy saving in wireless networks. The simulation results indicate that EAP-CMAC outperforms IEEE 802.11 and CoopMAC in terms of energy-efficiency by 35% and 100% respectively. Furthermore, the proposed optimal power allocation enhances EAP-CMAC performance in terms of network lifetime by 7% compared to equal power allocation.

Moreover in this study a cooperative Medium Access Control (MAC) protocol, called Cooperative Cognitive TDMA (CC-TDMA), is proposed for cognitive networks. The proposed protocol decides between energy harvesting, data transmission and relaying transmission. In this regard, licensed users lease part of their spectrum to unlicensed users to retransmit the failed packets on the licensed users' behalf. By doing so, the unlicensed users obtain greater opportunity for data transmission, thus increasing their performance. The simulation and analytical results indicate that the CC-TDMA significantly improves the throughput and Packet Drop Rate (PDR) of both licensed and unlicensed users compared to conventional TDMA.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

STRATEGY KAWALAN AKSES MEDIUM CEKAP TENANGA BAGI RANGKAIAN KOOPERATIF TANPA WAYER

Oleh

MAHMOUD SAMI

Ogos 2016

Pengerusi : Profesor Nor Kamariah Noordin, PhD
Fakulti : Kejuruteran

Komunikasi hijau baru-baru ini telah mendapat banyak perhatian, kerana ia bukan sahaja memberi jaminan Kualiti Perkhidmatan (QoS) dan mengurangkan penggunaan kos dan penggunaan tenaga, malah juga tidak berbahaya kepada alam sekitar. Anjakan paradigma ke arah komunikasi efficien-tenaga telah dipergiatkan dalam pelbagai pendekatan teknikal. Komunikasi koperatif telah diperkenalkan sebagai teknik transmisi efficien-tenaga yang berkesan, di mana nod antena tunggal digalakkan untuk berkongsi sumber dan membina sistem dasar Multi Input Multi Output (MIMO) , mengakibatkan keuntungan besar dalam pelbagai aspek dan produktiviti. Komunikasi koperatif dianggap sebagai penyelesaian yang berkesan untuk nod mudah alih di mana beberapa masalah dari segi saiz fizikal dan penggunaan tenaga yang timbul daripada pembinaan pelbagai antena. Walau bagaimanapun, faedah komunikasi koperatif akan dipandang remeh oleh protokol klasikal atasan yang direka bagi legasi sistem bukan koperatif.

Oleh itu, mengambil kira kerjasama daripada pihak atasan dan merekabentuk protokol MAC adalah penting. Kajian ini memperkenalkan protokol MAC koperatif baru yang dikenali sebagai EAP-CMAC (Energy Aware Physical-layer Network Coding Cooperative MAC) yang mengintegrasikan komunikasi koperatif ke dalam PNC dalam rangkaian ad-hoc tanpa wayar. Dalam EAP-CMAC, mod penghantaran yang terbaik dipilih antara penghantaran langsung, Koperatif klasikal dan penghantaran berasaskan PNC; dengan mempertimbangkan kualiti sambungan barisan destinasi dan destinasi sumber.

Selain itu, pilihan sambungan komunikasi dan peruntukan kuasa algoritma adalah dicadangkan berdasarkan informasi lokasi dan nod sisa tenaga yang meningkatkan jangka hayat rangkaian dan penjimatan tenaga dalam rangkaian tanpa wayar secara ketara. Keputusan simulasi menunjukkan bahawa EAP-CMAC melebihi IEEE 802.11 dan CoopMAC dari segi jangka hayat rangkaian sebanyak 35% dan 100%. Tambahan pula, peruntukan kuasa optimum yang dicadangkan meningkatkan prestasi EAP-CMAC dari segi jangka hayat rangkaian sebanyak 7% berbanding peruntukan kuasa yang sama.

Lebih-lebih lagi, dalam kajian ini protokol koperatif Medium Access Control (MAC), dipanggil juga sebagai Cooperative Cognitive TDMA (CCTDMA), dicadangkan untuk rangkaian kognitif. Dalam hal ini, pengguna yang berlesen memajak sebahagian daripada spektrum mereka kepada pengguna yang tidak berlesen untuk penghantaran semula paket yang gagal bagi pihak pengguna yang berlesen. Dengan berbuat demikian, pengguna yang tidak berlesen mendapat peluang yang lebih besar untuk penghantaran data, sekaligus meningkatkan prestasi mereka. Simulasi dan keputusan secara analitikal menunjukkan bahawa CC-TDMA meningkatkan daya produktiviti dan Packet Drop Rate (PDR) secara ketara, bagi kedua-dua pengguna berlesen dan tidak berlesen berbanding dengan TDMA konvensional.

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Last but not least, I would like to thank my wife, bahar sajjadi, and my family for all of their endless support, encouragement and love.

I certify that a Thesis Examination Committee has met on 23 August 2016 to conduct the final examination of Mahmoud Sami on his thesis entitled "Energy-Efficient Medium Access Control Strategy for Cooperative Wireless Networks" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACK	Acknowledgement
AF	Amplify and Forward
AP	Access Point
ARQ	Automatic Repeat reQuest
CC	Cooperative Communication
CDMA	Code Division Multiple Access
CR	Cognitive Radio
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
CSMA/CA	CSMA Collision Avoidance
CSMA/CD	CSMA Collision Detection
CTS	Clear To Send
CW	Contention Window
DCF	Distributed Coordination Function
DF	Decode and Forward
DIFS	Distributed Inter-Frame Space
EGD	Equal Gain Diversity
ITS	Intelligent Transportation System
LTE	Long Term Evolution
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network
MIMO	Multiple Input Multiple Output
MISO	Multi Input Single Output
MRC	Maximal Ratio Combining
NACK	Negative ACK
NAV	Network Vector Allocation
NC	Network Coding
NE	Nash Equilibrium
PHY	Physical Layer
PNC	Physical-Layer Network Coding
PU	Primary User

QoS	Quality of Service
RR	Relay Respond
RTS	Request to Send
SC	Selection Combining
SIFS	Short Inter-Frame Space
SINR	Signal to Noise and Interference Ratio
SNR	Signal to noise ratio
SU	Secondary Users
TDMA	Time Division Multiple Access
V2I	Vehicular to Infrastructure
V2V	Vehicular to vehicular
VANET	Vehicular Ad-hoc NETwork
WLAN	Wireless Local Area Network
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

The enormous growth of smart mobile devices in recent decades has prompted the emergence of new technologies that support high data transmission rates through reliable channels. For instance, the Global System for Mobile Communications (GSM) supports a maximum data rate of 10 Kbps, Wimax supports a maximum data rate of 150 Mbps and Long Term Evaluation (LTE) supports a maximum data rate of 300 Mbps. Although these technologies sustain maximum capacity and high data transmission rates, it comes at the cost of high energy consumption, particularly in dense networks with numerous users and heavy traffic loads. Thus, the power consumption and increasing demand for energy for wireless devices has led the way toward efficient data transmission for the next generation of wireless networks. Green communication has recently gained tremendous attention, as it not only guarantees Quality of Service (QoS) and minimizes cost and energy consumption, but it is also environmentally friendly. Cooperative communication has newly been introduced as an energy-efficient transmission technique that prevents numerous unsuccessful direct transmissions and significantly reduces energy wastage. The paradigm shift toward energy-efficient communication has intensified with respect to different communication matters, such as power control, resource management, cross-layer optimization and energy-aware protocol design [1, 2].

1.1 Background

Cooperative diversity is an energy-efficient transmission technique, where the terminal nodes are encouraged to share their resources and construct virtual Multi-input Multi-output (MIMO) antennas [3],[4]. Besides increasing diversity gain and throughput, this strategy is also energy-efficient in cases where mobile radio users suffer from time-varying channels for data transmission due to channel fading and various other channel qualities encountered. Although increasing SNR mitigates channel fading effects, it is at the cost of more power and energy consumption. As an alternative, cooperative diversity has emerged to combat channel impairment, energy limitations and radio spectrum constraints [5],[6]. In addition, employing MIMO techniques in some technologies such as sensor nodes, small mobile nodes and hand-held devices, is confined by physical size, hardware complexity and high energy consumption. In order to overcome such challenges, the mobile nodes share antennas and create a virtual MIMO system to achieve spatial diversity.

The vast majority of previous studies on cooperative communication have concentrated on various concerns and challenges with the physical layer as well as information-theoretic approaches [7],[8],[9]. Depending on how a relay node processes a received signal, various signalling methods are proposed, including Amplify and Forward (AF), Decode and Forward (DF) and Compress and Forward (CF). Since advances in wireless cooperative communication have introduced several available transmission patterns (e.g. direct transmission, relay transmission, two-hop transmission, network coding-based transmission, etc.), network capacity is potentially affected by various helper-assisted transmission patterns. In addition, the PHY (Physical Layer) and information theoretical approaches cannot explain certain network behavior, such as random packet arrival rate and dynamic traffic, which significantly influence the network MAC layer parameters (e.g. queuing delay, packet drop rate and throughput stability). The presence of relay nodes can improve system performance and channel conditions by either providing additional diversity gain or boosting the received signal SNR. The former can be achieved by employing multiple relays or combining techniques that merge the signals received from the source and relay. Thus, in order to attain the desired diversity gain through appropriate helper-assisted transmission or by implementing multiple-relay transmission, adequate scheduling is essential between relay nodes and source-destination to coordinate transmissions. Nevertheless, most previous works on CC have addressed rather simplified scenarios including three-party nodes (source/relay/destination) and assumed the presence of idle Medium Access Control (MAC), which accurately coordinates data transmission among users. However, the benefits of cooperative communication are degraded by traditional, higher-layer protocols designed for legacy non-cooperative systems. Thus, appropriate coordination and scheduling between nodes in the MAC layer is crucial to improve end-to-end performance and make cooperation more feasible and practical.

Generally, cooperative MAC protocols are divided into contention-based and contention-free (reservation-based) schemes. In contention-free protocols, each time slot is allocated to an individual node, thus the nodes do not contend with each other for channel access. However, this strategy generally suffers from dynamic network topology changes and transmission delay in dense networks. Contention-based protocols do not require complex coordination and are thus more robust against topology changes and face lower overhead and energy consumption in sparse networks. These benefits may decline with increasing traffic load due to corresponding increments in collisions that cause lots of energy wastage for retransmission and idle listening. In addition, bounded latency is not guaranteed in contention-based networks. Therefore, an appropriate scheduling and MAC protocol would not only prevent numerous retransmissions due to collisions but also reduce end-to-end communication latency.

1.2 Problem Statement

Medium Access Control (MAC) has the duty to efficiently share the available bandwidth amongst distributed users and coordinate their access to wireless channels. However, the presence of relay nodes makes cooperation in the MAC layer rather complex and imposes additional overhead to the system. In addition, some challenges with relay selection and resource allocation arise with MAC duties and cross-layer design in cooperative networks, which significantly influence protocol performance and MAC layer parameters. Therefore, it is essential to consider the impact of cooperation on higher layers and MAC protocol design, as the nodes' channel access should be accurately scheduled for collision-free transmission. Toward this aim, it is important to answer some questions from a MAC layer perspective rather than PHY, such as: When is cooperation beneficial? How to cooperate with other nodes? Which links are more efficient?

The majority of previous cooperative MAC protocols mostly focus on throughput improvement and delay reduction, but at the expense of higher energy consumption and network lifetime degradation. Moreover, users in a Mobile Ad-hoc NETwork (MANET) can connect through wireless links and communicate with each other while a critical concern regarding continuous connection in MANETs is network lifetime on account of battery and energy resource scarcity. In addition, the scarcity of wireless spectra has led to the emergence of a new technology called Cognitive Radio (CR). A combination of Cooperative Communication and CR further improves network performance. In order to facilitate cooperation between Secondary Users (SUs) and Primary Users (PUs) and to coordinate their channel access, an efficient cooperative MAC protocol is essential.

Accordingly, three main challenges need to be addressed as follows.

1. In order to exploit PNC in cooperative networks, an elaborate protocol is essential to satisfy the following two main challenges. First, a collision-free scheduling scheme is necessary to coordinate the simultaneous transmission of two end nodes. Secondly, the designed protocol should be compatible with traditional cooperative protocols to avoid redundant PNC-based transmission if either direct or conventional cooperative transmission is more effective.

2. A great challenge with mobile networks is with relay selection, whereby in dynamic networks, channel conditions and network topology frequently change, rendering relay selection harder. In this situation, relay selection not only poses significant signalling control overhead but also reduces MAC layer performance in the cooperative network. Thus, it is important to design an effective, fast and reliable relay selection algorithm for mobile networks.

3. In order to exploit energy harvesting nodes in cooperative cognitive networks, an effective channel access strategy is crucial. To this aim, an elaborate medium access should be designed to coordinate the nodes' channel access, cooperation and energy harvesting modes.

1.3 Aim and Objectives

The following three objectives comprise the principal aim of this thesis.

1. To design a novel cooperative MAC protocol in order to exploit Physical Layer Network Coding (PNC) in cooperative networks to improve energy-efficiency and throughput.

2. To design a joint relay selection and power allocation algorithm integrated in the cooperative MAC protocol (EAP-CMAC) that improves network lifetime by adjusting the power transmission needed in order to meet the required system QoS.

3. To design a cooperative MAC protocol by exploiting splitting technique that decides between energy harvesting and data transmission in cognitive networks. By doing so, secondary users enter in a cooperation to retransmit the primary users' failed data and obtain more opportunity for data transmission.

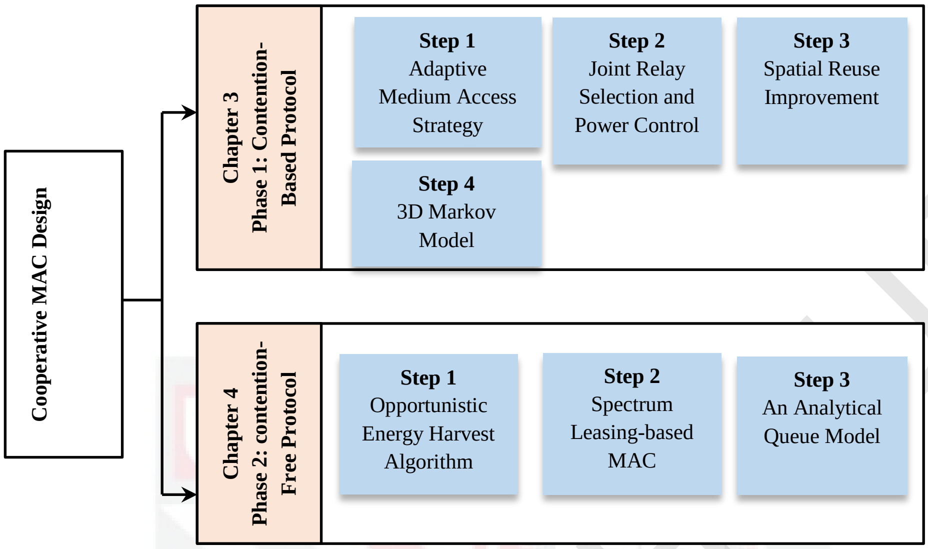

Figure 1.1: Methodology Steps

1.4 Contribution of the Thesis

B) A new relay selection algorithm is proposed to find the best relay based on the terminal nodes' residual energy. Accordingly, a detailed power allocation is designed to provide the required QoS.

C) A 3D Markov model is developed to analyse the cooperative protocols (EAP-CMAC) and consider the probability of successful transmission in the network.

D) An accurate Network Allocation Vector (NAV) setting is provided for spatial reuse enhancement. The simulation and analytical analysis illustrate that EAP-CMAC improves network lifetime significantly more than traditional cooperative MAC protocols and legacy IEEE 802.11.

E) A new cooperative MAC protocol is designed for cognitive networks, whereby users harvest energy from RF signals to charge their batteries for data transmission. The proposed protocol guarantees the Quality of Service (QoS) needed by the primary network.

1.5 Methodology

In order to design an energy-efficient cooperative MAC protocol for wireless communication networks, two different channel access strategies are considered, including contention-based and contention-free schemes (Figure 1.1). In phase 1 (Chapter 3), a contention-based medium access strategy is assumed for Mobile Ad Hoc Networks. The system performance is subsequently devolved in 4 steps. In the first step, an adaptive cooperative medium access strategy is proposed. This algorithm selects the best transmission strategy among direct transmission, traditional cooperative transmission and PNC-based transmission. In the second step, a joint relay selection and power allocation algorithm is proposed, which concerns energy consumption. This algorithm is based on residual energy of mobile users, selects the best relay node and allocates optimal power to the relay and source nodes for data transmission. This strategy improves network lifetime by more than 7% compared to equal power allocation. Spatial frequency reuse can be affected by cooperative communication, where the relay node expands the interference zone of the current transmission and blocks neighboring nodes' transmissions. The effect of cooperation on spatial frequency reuse is also worth noting. Consequently, in the third step, a spatial reuse scheme is proposed that increases the number of concurrent transmissions, improves bandwidth utilization and reduces transmission delay.

In the second phase (Chapter 4), contention-free strategies are investigated. At this point, a cooperative MAC protocol is proposed to improve cognitive network performance. The proposed strategy enhances network performance in 3 stages. First an opportunistic energy harvesting algorithm is used to design a cooperative MAC protocol. In this algorithm nodes decide between energy harvesting and data transmission. Second, a leasing-based cooperative medium access control strategy is recommended, in which secondary users decide between energy harvesting mode and transmission mode. In this regard, primary users lease a part of their spectrum to secondary users in exchange for benefits. In the third stage, a Markov model is suggested, which considers the rate of packet arrival to users and analyses the network performance when the proposed protocols are in operation.

1.6 Contribution of the Thesis

In this thesis, cooperative communication is investigated from medium access control layer perspective. Various methodologies are proposed in order to improve the energy efficiency of cooperative communication in wireless networks. The rest of the thesis is organized as follows:

Chapter 2: Literature Review and Taxonomy

Chapter 2 presents a comprehensive survey and classification of state-of-the-art cooperative MAC protocols. The requirements, challenges and solutions for designing effective cooperative MAC protocols are first considered. Next, a classification based on network applications is provided. In this part, the requirements and characteristics of cooperative MAC protocols in different networks (e.g. vehicular, cognitive, multi-hop, etc.) are investigated. Well-known cooperative MAC protocols are then classified according to transmission strategy into contention-based and contention-free protocols. The pros and cons, and framework of each protocol are also investigated.

Chapter 3: An Energy-Aware Cross-Layer Cooperative MAC for Mobile Ad-Hoc Networks

A novel energy-aware cross-layer cooperative MAC is proposed in Chapter 3. This protocol integrates physical layer network coding (PNC) into cooperative communication and offers the best transmission mode among direct, traditional and PNC-based transmissions. Energy efficiency and network lifetime are considered important metrics in designing a cross-layer MAC. In addition, a joint relay selection and power allocation algorithm is proposed to improve network lifetime. This protocol is briefly evaluated using both analytical models and simulation tools.

Chapter 4: A TDMA-Based Cooperative MAC Protocol with Opportunistic Energy Harvesting for Cognitive Networks

Chapter 4 introduces energy harvesting as a solution for saving energy and expanding network lifetime. The preliminaries and main structure of energy harvesting networks are initially presented. Next, a TDMA-based cooperative MAC protocol for cognitive networks is offered, whereby secondary users (SUs) start cooperation with primary users (PUs) in order to increase throughput. By doing so, the SUs obtain greater opportunity to transmit their own data. In this protocol, both PUs and SUs select the best strategy to harvest energy from RF signals, resulting in higher network performance. The proposed protocol outperforms conventional TDMA protocols in terms of throughput and Packet Drop Rate (PDR).

Chapter 5: Summary, Conclusion and Recommendation for Future Research

The last chapter concludes with the thesis results and achievements, followed by a list of recommendations for future work.

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