Cooperative Medium Access Mechanisms and Service-oriented Routing in Multi-hop Wireless Networks

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Cooperative Medium Access Mechanisms and Service-oriented Routing in Multi-hop Wireless Networks

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Preface and Acknowledgements

This dissertation is a result of my four years (August 2007 - July 2011) research carried out at the Agder Mobility Laboratory, Department of Information and Communication Technology (ICT), University of Agder (UiA) in Grimstad, Norway. The monumental task of crossing the finishing line of this dissertation involved the technical and emotional contributions of many individuals. I would, therefore, like to take this opportunity to express my gratitude to them.

First of all, I would like to thank my primary supervisor, Professor Frank Y. Li for his continuous guidance, criticism, active involvement, encouragement, and constant support of my work. I would also like to express my thanks towards Professor Frank Reichert, my co-supervisor, for his suggestions and encouragement during my study.

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I would like to thank the excellent support of my colleagues at UiA, Ram Kumar, Andreas Häber, Lei Jiao, Ziaul-Haq Abbas, Yuanyuan Ma, and Batool Talha for numerous discussions and valuable feedback. I am indebted to many more of my friends, colleagues and students at UiA, whose company and discussion have made my duration of study memorable and fruitful. I would especially appreciate the assistance provided by the Coordinator of the PhD program in the Department of ICT at UiA, Mrs. Trine Tønnessen, as well as Tor Erik Christensen, from International Education Office.

Last but not least, I would like to thank my parents and my uncle for their support and encouragement, for their patience and commitment for helping me through the harder periods of my work. On a concluding note, the quote below is dedicated to the people who have helped to inspire and encourage me in pursing this degree, personally and/or professionally along the way.

”There is no such thing as a ’self-made’ man. We are made up of thousands of others. Everyone who has ever done a kind deed for us, or spoken one word of encouragement to us, has entered into the make-up of our character and of our

thoughts, as well as our success.”

- George Matthew Adams

Hongzhi Jiao
July 2011
Grimstad, Norway

Abstract

Multi-hop wireless networks have been regarded as a promising path towards future wireless communication landscape. In the past decade, most related work has been performed in the context of mobile ad hoc networks. In very recent years, however, much effort has been shifted to more static networks such as wireless mesh networks and wireless sensor networks. While significant progress has been achieved through these years, both theoretically and experimentally, challenges still exist in various aspects of these networks. For instance, how to use multi-hop networks as a means for providing broadband Internet services with reliability and balanced load remains as a challenging task. As the number of end-users is increasing rapidly and more and more users are enjoying multimedia services, how to provide Quality of Service (QoS) with user satisfaction in such networks remains also as a hot topic.

Meanwhile, another direction which has recently attracted lots of efforts in the international research community is the introduction of cooperative communications. Cooperative communications based on relaying nodes are capable of improving network performance in terms of increased spectral and power efficiency, extended network coverage, balanced QoS, infrastructure-less deployment, etc. Cooperation may happen at different communication layers, at the physical layer where the received signal is retransmitted and at the MAC and routing layers where a packet is forwarded to the next hop in a coordinated manner towards the destination, respectively. However, without joint consideration and design of physical layer, MAC layer and network layer, the benefit of cooperative communication cannot be exploited to the maximum extent. In addition, how to extend one-hop cooperative communication into multi-hop wireless network scenarios remains as an almost un-chartered research frontier.

In this dissertation, we enhance the state of the art technologies in the field of multi-hop wireless networks from a layered perspective. While efficient scheduling mechanisms are proposed at the MAC layer, elaborate routing protocols are devised at the network layer. More specifically, by taking into account of cross layer design we cope with network congestion problems in wireless mesh networks mainly at the network layer. In order to further improve the performance of cooperative wireless networks, we propose a contention-based cooperative MAC protocol in the presence of multiple relay nodes. Since a large majority of existing cooperative MAC protocols are designed based on widely-used IEEE 802.11 MAC protocol which exhibits inherent design constraint when applied in multi-hop wireless networks, it is imperative to develop a novel cooperative MAC protocol which is appropriate for multi-hop network scenarios. Next, we propose a TDMA-based MAC protocol

supporting cooperative communications in static multi-hop wireless networks. Furthermore, a cooperative lifetime maximization MAC protocol is proposed to cope with the energy hole problem in wireless sensor networks.

List of Publications

The purpose of this list is to keep a record of all the papers as an outcome of the research work carried out by the author of this dissertation. The list of publications comprises of both accepted and already published papers, organized in two sets.

Set I: Papers Included in this Dissertation

This section consists of the following five papers:

Paper A H. Jiao and F. Y. Li, A Novel Traffic Splitting Policy for Performance Improvement in Wireless Mesh Networks, *in Proceedings of the 15th European Wireless 2009 (EW 2009)*, Aalborg, Denmark, May 2009.

Paper B H. Jiao and F. Y. Li, A Contention-based Multiple Access Protocol in Cooperative Wireless Networks, *in Proceedings of the 6th ACM International Wireless Communications & Mobile Computing Conference 2010 (IWCMC 2010)*, Caen, France, Jun. 2010

Paper C H. Jiao and F. Y. Li, Cooperative MAC Design in Multi-hop Wireless Networks - Part II: When Source and Destination are Two-hops away from Each Other, *Wireless Personal Communications, Springer*, vol. 57, no. 3, pp. 351-363, 2011

Paper D H. Jiao and F. Y. Li, A TDMA-Based MAC Protocol Supporting Cooperative Communications in Wireless Mesh Networks, *International Journal of Computer Networks & Communications (IJCNC)*, AIRCC, vol. 3, no. 5, pp. 21-38, Sep. 2011.

Paper E H. Jiao, M. A. Ingram, and Frank Y. Li, A Cooperative Lifetime Extension MAC Protocol in Duty-Cycle Enabled Wireless Sensor Networks, *the 30th IEEE MILCOM conference 2011*, Baltimore, MD, USA, Nov. 2011.

Set II: Papers Not Included in this Dissertation

The papers listed below are complementary to those mentioned in Set I. They are, however, not reproduced as a part of the dissertation in order to focus on the most significant contributions of this thesis work.

Paper G H. Jiao and F. Y. Li, A Service-Oriented Routing Scheme with Load Balancing in Wireless Mesh Networks, *in Proceedings of the IEEE International Symposium on Wireless Communication Systems 2008 (ISWCS 2008)*, Reykjavik, Iceland, Oct. 2008.

Paper H H. Jiao, F. Y. Li, V. Oleshchuk, and X. Zheng, An Enhanced Reputation-Based Scheme for Securing OLSR, *in Proceedings of Norwegian Information Conference 2008 (NIK 2008)*, Kristiansand, Norway, Nov. 2008.

Paper I H. Jiao and F. Y. Li, Cooperative Medium Access Control in Wireless Networks: the Two-hop Case, *in Proceedings of the 5th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications 2009 (WiMob 2009)*, Marrakech, Morocco, Oct. 2009.

Paper J H. Jiao and F. Y. Li, An Adaptive Cooperative MAC Mechanism in Multi-hop Wireless Networks, *in Proceedings of the 15th IEEE Symposium on Computers and Communications 2010 (ISCC 2010)*, Riccione, Italy, June 2010.

Paper K H. Jiao and F. Y. Li, A Mini-Slot-based Cooperative MAC Protocol for Wireless Mesh Networks, *in Proceedings of the IEEE International Workshop on Heterogeneous, Multi-Hop, Wireless and Mobile Network 2010 (HeterWMN 2010), in the conjunction with IEEE Global Telecommunications Conference (GLOBECOM)*, Miami, FL, USA, Dec. 2010

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Abbreviations

4G	Fourth Generation
5G	Fifth Generation
ACK	Acknowledgement
AF	Amplify-and-Forward
AMC	Adaptive Modulation Coding
AODV	Ad-hoc On-demand Distance Vector
AP	Access Point
ARQ	Automatic Repeat reQuest
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BRP	Border Resolution Protocol
BS	Base Station
CFC	Call For Cooperation
CRC	Cyclic Redundancy Code
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CSI	Channel State Information
CT	Cooperative Transmission
CTP	Collection Tree Protocol
CTS	Clear To Send
CW	Contention Window
DCF	Distributed Coordination Function
DF	Decode-and-Forward
DIFS	DCF Interframe Space
DSDV	Destination-Sequenced Distance-Vector
DSR	Dynamic Source Routing
DSTC	Distributed Space-Time Coding
ETT	Expected Transmission Time
ETX	Expected Transmission Count

GPS	Global Positioning System
GTS	Guaranteed Time Slots
HNA	Host and Network Association
IARP	Intrazone Routing Protocol
IERP	Interzone Routing Protocol
IETF	Internet Engineering Task Force
IGW	Internet Gateway
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MID	Multiple Interface Declaration
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MPR	Multipoint Relay
MR	Mesh Router
MRC	Maximal Ratio Combining
MRP	Multiple Relay Point
MPDU	MAC Protocol Data Unit
NAV	Network Allocation Vector
NDP	Neighbor Discovery Protocol
OFDM	Orthogonal Frequency Division Multiplexing
OLSR	Optimized Link State Routing
OSI	Open System Interconnection
PCF	Point Coordination Function
PER	Packet Error Ratio
PLCP	Physical Layer Convergence Protocol
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RFC	Request for Comments
RREP	Route Reply
RREQ	Route Request
RRER	Route Error
RTR	Request to Receive
RTS	Ready to Send
SIFS	Short Interframe Space
SISO	Single Input Single Output

SNR	Signal-to-Noise Ratio
STBC	Space-Time Block Coding
STC	Space-Time Coding
TC	Topology Control
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network
WOSPF	Wireless Open Shortest Path First
WSN	Wireless Sensor Network
ZRP	Zone Routing Protocol

PART I

Chapter 1

Introduction

1.1 Multi-hop Wireless Networks

Wireless communications provide no doubt very attractive services as demonstrated by the tremendous growth in both cellular systems and Wireless Local Area Networks (WLANs). However, these two radically different technologies do not cover the full spectrum of service needs, and there are numerous other applications that can benefit from broader wireless connectivity. Cellular networks offer wide area coverage, but the service is relatively expensive and offer relatively low data rates. On the other hand, WLANs have rather limited coverage, but provide comparatively high data rates. In order to increase the coverage of WLANs, a new category of wireless network where a wired or wireless backbone connects multiple access points has merged recently, in the form of multi-hop communications.

In multi-hop wireless networks, there are one or more intermediate nodes along the path that are interconnected by means of wireless links. Compared with networks with single wireless link, multi-hop wireless networks have serval benefits. First of all, multi-hop wireless networks could extend the coverage of a network and improve network connectivity. In addition, nodes in such a network, which are usually self-configured and self-organized, communicate with each other over multiple hops by running a distributed routing protocol. This feature enables multi-hop wireless networks to be deployed in a cost-efficient way, avoiding wide deployment of cables which is costly. Furthermore, in a multi-hop wireless network, multiple paths may become available, resulting in much higher robustness of the network. Therefore, multi-hop wireless networks have been deemed as a promising network technology for future wireless communications. Examples of such network include Mobile Ad Hoc Networks (MANETs) [1], Wireless Mesh Networks(WMNs) [2–4] and Wireless Sensor Networks (WSNs) [5].

While MANETs appear more dynamic due to node mobility, the network topology for WMNs and WSNs remains comparatively stable. The topology of a multi-hop wireless network is the set of communication links between node pairs used explicitly or implicitly by a routing protocol. Since network topology depends on ”uncontrollable” factors such as node mobility, interference, noise, as well as on ”controllable” parameters such as transmission power and antenna direction, these networks are vulnerable to topology change [6]. In addition, due to the shared nature of the wireless medium in these networks, mutual interference among nodes cannot be avoided, especially when the nodes are hidden from each other [7, 8]. Nevertheless, even with these difficulties, multi-hop wireless networks still continue to attract increasing attention owing to its easy deployment with infrastructure-less communications and wide range of applications. Such applications include peer-to-peer communications, natural disaster recovery operations, metropolitan area networking and so on. However, before these new applications can be realized, it is necessary to gain insight into how such networks could be deployed and provide reliable and efficient services to end users.

1.2 Cooperative Communications

By exploiting time and spatial diversity, cooperative communication has emerged as a promising technique to enhance system performance in wireless networks. Spatial diversity is typically achieved by using multiple antennas at both the transmitter and the receiver sides. Recently, Multiple Input and Multiple Output (MIMO) communication systems and the corresponding channel coding techniques which are targeted to increase spectrum efficiency (in bps/Hz) and to improve the robustness of the wireless link, have been proposed to implement space diversity in the next generation wireless networks [9–17]. However, all these improvements come at the the cost of multiple Radio Frequency (RF) front ends at both the transmitter and the receiver. Furthermore, the number of antennas implemented on small mobile devices might be constrained due to device size and energy constraints. In order to overcome this practical problem of MIMO systems, cooperative communication enables single-antenna device in a multi-user environment to share their antennas and form a virtual multiple-antenna transmitter that allows them to achieve diversity without the requirement of additional antennas at each device. Therefore, while MIMO systems are regarded as a key technology to improve the performance and capacity of wireless communications over conventional single antenna systems, the concept of cooperative communications has been recently considered as a solution to exploit the potential MIMO gains in a distributed manner.

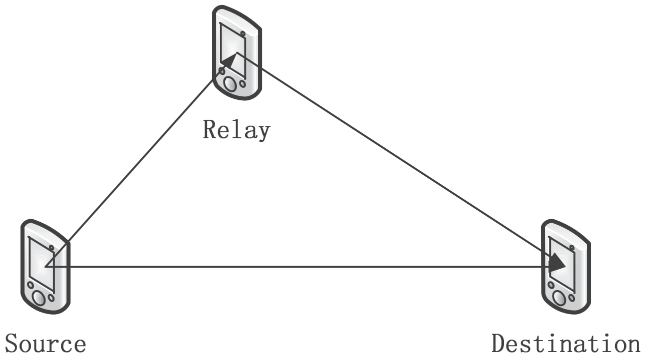

Figure 1.1: Illustration of cooperative transmission.

In a cooperative communication environment, different nodes can share resources to distribute the phases of transmission and/or processing. As demonstrated in Fig. 1.1, a source node transmits packet to a destination node. If the packet is not successfully received by the destination, a relay node around the source and the destination which overhears the direct transmission will retransmit the overheard packet to the destination[1]. This triangle communication portrays the essence of wireless cooperative communications, i.e., the source node achieves reliable communication to the destination through the help of intermediate neighbor node. As we know, wireless channels may suffer from fading, meaning that the signal attenuation can vary significantly over the course of a given transmission. Transmitting different copies of the same message could generate diversity and efficiently combat channel fading. In particular, spatial diversity relies on the principle that signals are transmitted from geographically separated transmitters, leading to independently faded versions of the same signal at the receiver. As a consequence, the benefits of cooperative communications include:

- Enhanced communication reliability over time-varying channels;
- Improved system throughput, reduced communication delay and number of retransmissions across the network;
- Reduced transmission power, decreased interference, and improved spatial frequency reuse;
- Enlarged transmission range, extended network coverage and prolonged network lifetime.

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[1] In some cooperative schemes, the source and the relay may transmit simultaneously.

It is worth mentioning that cooperative communication has found applications in various networks ranging from cellular networks, wireless ad hoc networks, to wireless sensor networks, etc. [18–26]. However, although cooperative systems exhibit so many advantages, there are still open issues that need to be addressed. In cooperative communication networks, the relay traffic, signaling overhead, end-to-end latency as well as interference will increase. It is thus imperative for cooperative system designers to carefully analyze the shortcomings of cooperative communication systems. Designers should propose strategies that facilitates in exploiting the benefits of cooperative communications to their full extend. The development of such cooperative communication systems is, nevertheless, not possible without a profound knowledge of cooperative communication technology across multiple protocol layers in a network architecture.

The theoretical and implementation aspects of cooperative diversity at the physical layer have become an intense field of research during the the past decade [23, 27–35]. For instance, many studies have paid attention to the outage probability for different types of fading channels, and others exploit cooperative diversity by improving bit error rate, which could lead to reliable transmission. The channel capacity of cooperative networks was investigated in [36–39]. Several cooperation protocols have been proposed, e.g. amplify-and-forward and decode-and-forward protocols [40–42], user cooperation protocol [43, 44], and coded cooperation protocol [27]. However, the impact of cooperative techniques on the upper layers of communication protocols has not been thoroughly studied so far. In practice, cooperative gain may disappear if higher layer protocols are not properly designed. In addition, how to perform cooperative communications in a multi-hop wireless network remains as a challenging task due to more complicated network environments and constraints. Therefore, in order to build a fully cooperative network, research at the physical layer should be coupled with higher layers of the protocol, in particular, the MAC layer (and the network layer). In the meantime, different cooperative communication protocols are needed to meet the requirements of diverse systems.

1.3 Research Objectives and Methodology

The objective of this dissertation is to study the mechanisms and protocols in multi-hop wireless networks and to propose novel schemes to improve the performance of these networks. The distinct features and critical design factors of multi-hop wireless networks bring many challenging issues to communication protocols, ranging from the application layer down to the physical layer. Despite recent advances in the research and development in MANETs, WMNs, and WSNs, many challenging problems still remain, e.g., protocols in various layers need to be improved, advanced physical layer techniques need to be implemented through higher layer protocols' support, new schemes are required for network management, protocols should work in an energy efficient way. In this thesis, we attempt to answer the following important questions:

- Question 1: How to improve network performance for wireless mesh networks, especially under traffic congestion status?
- Question 2: What is the benefit of applying cooperative communication in wireless networks? And how to design a cooperative MAC protocol in the presence of multiple relay nodes?
- Question 3: How to achieve cooperative gain and extend it to a multi-hop wireless network scenario?
- Question 4: Given static network topology, how to design cooperative MAC protocols based on Time Division Multiple Access (TDMA) principle?
- Question 5: How to integrate cooperative transmission into a duty cycle MAC protocol in wireless sensor networks?

Based on the above research questions, a detailed literature review was performed, existing solutions were surveyed, and the potential technologies were investigated. Historically, engineers have partitioned solutions of those problems into a stack of protocol layers, each serving a particular purpose. Fig. 1.2 illustrates these layers and indicates the functions they usually serve in communication networks. For instance, the physically layer conventionally combats fading with coding, spread-spectrum. The MAC layer normally handles access to the shared medium and manages protocol access to the physical medium. Layering promotes the development of understanding and technology within each layer. However, some issues have to be addressed at various layers. For example, cooperative communications involve various aspects of the physical, medium access control and even network layers. Returning to Fig. 1.2, we introduce two solutions, load balancing and cooperative communications, to improve network performance. While load balancing being engaged from layer 2 to layer 4 perspective is mainly used to deal with congestion problems in the network, cooperative communications being exploited at the physical and MAC layers are expected to improve network performance significantly from various aspects. To address the research questions, the following research goals were identified:

- Goal 1: To explore routing protocols and metrics to cope with network congestion problems, especially from a cross layer perspective.
- Goal 2: To propose a contention-based cooperative MAC protocol and construct a theoretical basis intended for analyzing the benefits of the proposed protocol.
- Goal 3: To develop novel MAC schemes for various identified multi-hop wireless network scenarios.
- Goal 4: To develop a functional TDMA MAC protocol on the basis of providing cooperative communication in a static multi-hop wireless network.
- Goal 5: To develop an energy-efficient MAC protocol to schedule sensor nodes in a cooperative manner that nodes wake up and sleep alternately to maximize the wireless sensor network lifetime.
- Goal 6: To construct theoretical models to analyze network protocols, as well as setting up simulation environments to evaluate system performance.

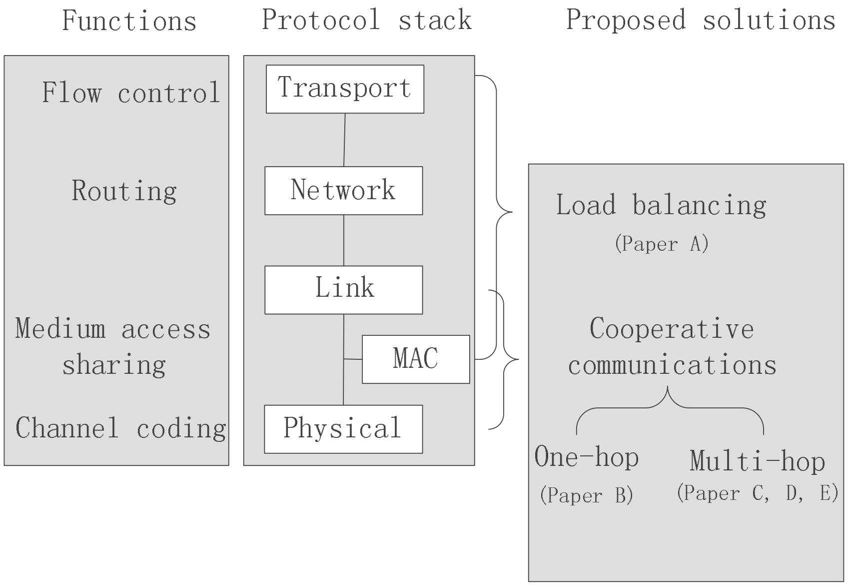

Figure 1.2: Outline of research approaches.

Table 1.1 illustrates the mapping batween the research goals and research questions. The research goals are achieved through the scientific contributions of the thesis which include Part I of the thesis and Papers A-E. The details of how research goals are addressed in scientific contributions are discussed in Chapter 5.

Table 1.1: Mapping of research goals and research questions.

Research Goal	**Research Questions**
Goal 1	Question 1
Goal 2	Question 2
Goal 3	Question 3
Goal 4	Question 4
Goal 5	Question 5
Goal 6	Questions 1-5

1.4 Organization of the Dissertation

The dissertation is grouped to two parts, where Part I consists of Chapters 1-6 and provides an overview of the PhD work. Part II consists of Papers A-E. The connection between different papers on which the whole dissertation is built up is elaborated in Fig. 1.3.

- **Chapter 2** contains a comprehensive overview of wireless mesh networks, as well as corresponding routing protocols and routing metric. In order to improve the network performance, we propose a cross layer strategy to identify network congestion status and balance load when necessary.

- **Chapter 3** introduces cooperative communications and corresponding protocols, e.g., cooperative relaying protocols and cooperative diversity algorithms. Since the benefit of cooperative communication is derived through relay nodes, we present the state-of-the-art techniques for relay selection issues.

- **Chapter 4** presents various cooperative MAC protocols, based on single hop and multi-hop transmissions, different MAC classifications, and different network scenarios, e.g., wireless mesh networks and wireless sensor networks.

- **Chapter 5** provides a summary of the papers in Part II of the dissertation.

- **Chapter 6** concludes the main contributions of this dissertation.

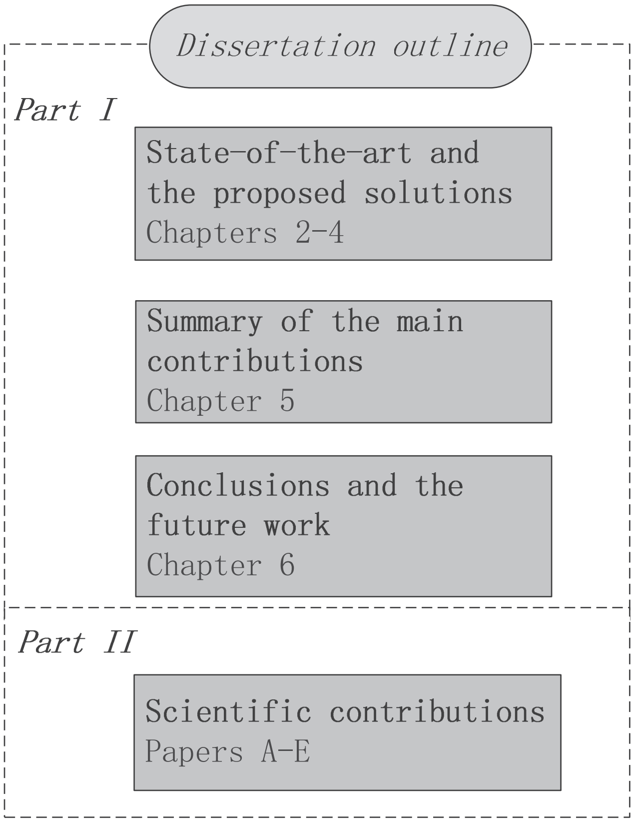

Figure 1.3: Outline of the dissertation.

Chapter 2

Routing and Load Balancing in Wireless Mesh Networks

2.1 Introduction

Wireless mesh networks have recently gained a lot of popularity represented by large scale deployments, thanks to their attractive features like large coverage and flexible scalability. While in ad hoc networks nodes may be battery powered and with high mobility, in WMNs most of the routers are either stationary or minimally mobile and do not relay on batteries. Hence the focus of routing algorithms is on improving network reliability and configurability as well as system performance, instead of dealing with mobility and minimizing energy consumption. This chapter intends to give a brief overview of the state-of-the-art strategies for a few aspects relevant to routing in wireless mesh networks. A variety of routing schemes and techniques are introduced. Routing schemes may be optimized for different demands, for instance, throughput, power consumption and link quality. Among several possible paths between a pair of nodes, the best route is selected according to certain routing metric.

2.2 Wireless Mesh Networks

WMNs build a multi-hop wireless backbone to interconnect isolated Local Area Networks (LANs) and to provide access for users who are not within the coverage of conventional access points. As shown in Fig. 2.1, a typical WMN can be envisaged to consist of a three level hierarchical structure. At the top of the hierarchy there are Internet Gateway (IGW) or gateway nodes that are directly connected with the global Internet. The second level of hierarchy is formed of nodes called Mesh Routers (MR) which have the same functionality of an access point, allowing regular stations (STAs) access to the wireless infrastructure. In addition, MR are connected to each other through multi-hop wireless links in order to forward each other' traffic towards the IGW. These MRs form the backbone of a WMN. At the lowest level of the hierarchy there are Mesh Clients which are end-users covered by MRs for accessing network services. For accessing Internet services, data packets generated from these mesh clients are relayed by intermediate MRs hop-by-hop and delivered to the global Internet in the end through the gateways. As an example, the IEEE 802.11s WMN standard is inherently developed based on the IEEE 802.11 standard to allow inter-operability between heterogeneous mesh network devices.

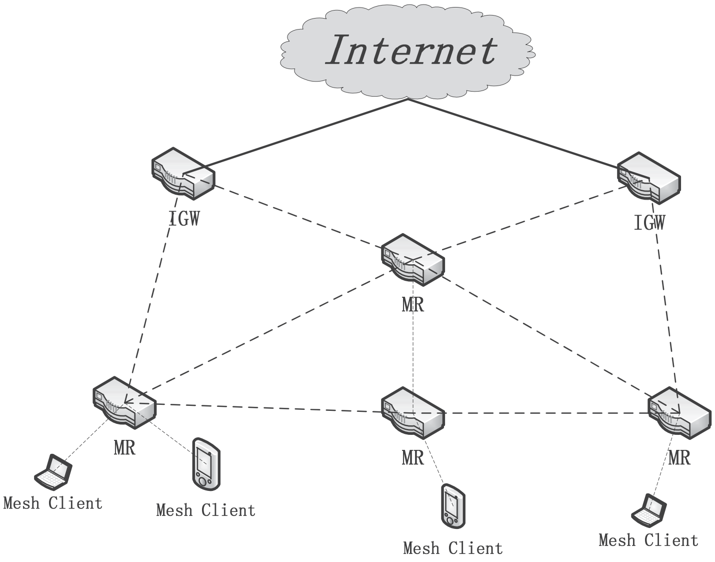

Figure 2.1: Hierarchical structure of wireless mesh networks.

Consequently, instead of being merely another type of ad hoc networking, WMNs diversify the capabilities of ad hoc networks. While the number of nodes in MANETs is equal to the number of routers, in WMNs the number of routers is much fewer than the number of nodes since mesh clients does not need to install routing protocols. While MANETs usually do not relay on any infrastructure, WMNs rely on infrastructure, but exhibit ad hoc features. Another main difference between WMNs and other multi-hop wireless networks such as mobile ad hoc networks and sensor networks is that the routers in WMNs are static and typically not power-constrained. This shifts the focus of routing from dealing with mobility to finding high throughput routes.

2.3 Routing Basics

Most routing protocols in wireless mesh networks are derived from mobile ad hoc networks. Mobile ad hoc networks are collections of mobile nodes that can dynamically form temporary networks without the need for pre-existing network infrastructure or centralized administration. These nodes can be arbitrarily located and can move freely at any given time. Because of this dynamic nature of the topology and environment in ad hoc networks, making a routing decision and maintaining the connectivity should be done in a smarter way than simply choosing the conventional shortest path, in order to deliver an acceptable level of Quality of Services (QoS) to suit the different needs of applications. Therefore, routing protocols adopted for fixed networks, such as traditional link-state and distance vector routing algorithms in their original forms are not effective in this environment due to heavy overhead. Numerous routing protocols have been proposed for mobile ad hoc networks. Which routing protocol to use in a particular scenario depends on application requirement and other aspects of the network, such as network size, node density, network topology and node mobility, etc.

2.3.1 Routing Protocols

Ad hoc routing protocols can be broadly classified as being proactive (table-driven) or reactive (on-demand). Other proposals using a hybrid approach which combine both proactive and reactive routing protocols have also been suggested.

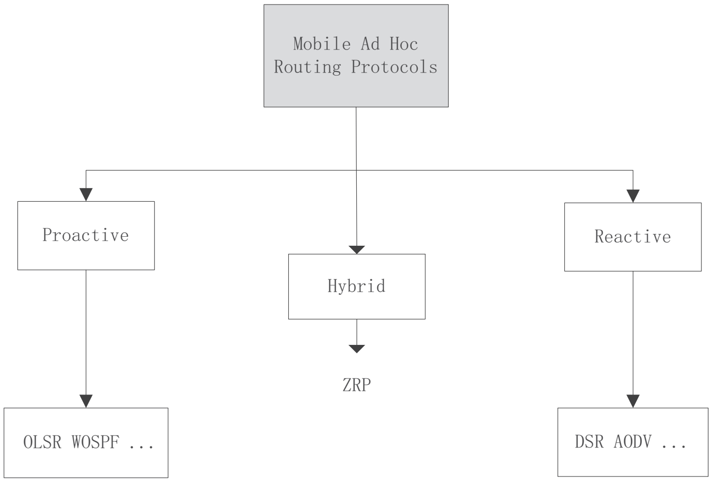

Figure 2.2: Categorization of ad hoc routing protocols.

Proactive routing protocols attempt to maintain consistent, up-to-date routing information from each node to every other node in the network. These protocols require each node to maintain one or more tables to store routing information, and they respond to changes in network topology by propagating route updates throughout the network to maintain a consistent network view. Examples of proactive algorithms are: Destination-Sequenced Distance-Vector Routing (DSDV), Wireless Open Shortest Path First (WOSPF) protocol, Optimized Link State Routing (OLSR) [45] , and so on.

OLSR is the most popular representative of such protocols. In a link state protocol, all link-states with neighbor nodes are declared and flooded across the network. OLSR is an optimized link state protocol for MANETs. In order to reduce overhead, each node selects a set of Multipoint Relays (MPRs) from its set of one-hop neighbors such that all two-hop neighbors can be reached through at least one of them. Since only MPRs forward protocol packets, flooding of protocol traffic is minimized. More specifically, four types of messages, HELLO, Topology Control (TC), Multiple Interface Declaration (MID), and Host and Network Association (HNA), are defined in OLSR. HELLO messages are used used for nodes to broadcast their link status to neighbors and used for MPR selection. TC messages disseminate topology information throughout the network. Note that only MPRs generate TC messages. The minimal set of link state information is the set of links between MPRs and their selectors. Routing tables are calculated based on the link state information exchanged through HELLO and TC messages. MID messages declare a list of interface addresses in case nodes participating in an OLSR routing domain have multiple interfaces. That means that they can run OLSR on multiple communication interfaces using multiple identifiers. HNA messages are employed to provide connectivity from the OLSR interfaces to those non-OLSR interfaces, e.g. the Internet.

OLSR is designed to work in a completely distributed manner and thus does not depend on any central entity. It does not require a reliable transmission for its control messages since each node sends its control messages periodically, leading to a subsistence of a loss of some packets from time to time.

In addition to OLSR, WOSPF is another representative of proactive link state routing protocol. It operates in a similar way as the OSPF protocol [46], which is widely deployed in the domain of fixed networks as an interior routing protocol. There have been three active WOSPF standards [47–49], respectively. The approach proposed in [48] is often referred to as WOSPF MANET Designated Router (WOSPF-MDR), and the approaches proposed in [47] and [49] are based on the concept of MPR. MPR in WOSPF-MPR is working in the same way as it does in

OLSR. WOSPF-MDR is based on the selection of a subset of MANET routers, consisting of MANET MDRs and Backup MDRs. The MDRs form a Connected Dominating Set (CDS), and the MDRs and Backup MDRs together form a bi-connected CDS for robustness. This CDS is exploited in two ways, flooding reduction and adjacency reduction, respectively.

Reactive routing protocols are also known as On-Demand Routing protocols, which follow the idea that each node tries to reduce routing overhead by sending routing packets only when a data packet is ready for transmission. In other words, reactive routing does not keep a record of all routes available in a network. This makes the system more lightweight. Concretely, reactive routing first has a route discovery phase in the way that source node floods a query packet into the network in order to search for a path. This phase is completed when a route is found or when possible paths from source node are searched within a specific time-to-live threshold. When a route is established, it is maintained while in use. If any link fails, the failure will be reported to the source and then another route discovery is triggered. Examples of reacting routing protocols are Ad Hoc On Demand Distance Vector Routing (AODV) [50] protocol, and Dynamic Source Routing(DSR) [51], etc.

AODV routing protocol is basically a combination of DSDV and DSR [52]. It borrows the basic on-demand mechanism of route discovery and route maintenance from DSR, plus the use of hop-by-hop routing, sequence numbers, and periodic beacons from DSDV. AODV aims at minimizing the number of required broadcasts by creating routes only on-demand, as opposed to maintaining a complete list of routes, like in DSDV. When a route to a new destination is needed, the node broadcasts a Route Request (RREQ) packet to find a route to the destination. Each node receiving a RREQ packet caches a route back to the originator of the request. Once the RREQ reaches the destination or an intermediate node with a fresh enough route to the destination, the destination or intermediate node responds by unicasting a Route Reply (RREP) packet back to the originator of RREQ. As RREP is routed back along the reverse path, nodes along the path set up forward route entries in their route tables that point to the originator. If RREQ times out without a corresponding RREP, the originating node increases the time-to-live gradually until a RREP is received or until a threshold is reached. Since RREP is forwarded along the path established by the RREQ, AODV only supports symmetric links. When a link break is found, a Route Error (RRER) message notifies other nodes that the destination is no longer reachable.

Hybrid routing protocols. Proactive protocols have the advantage that a node experiences minimal delay whenever a route is needed as a route is immediately available from the routing table. However, proactive protocols may not always be appropriate as they continuously use a substantial fraction of the network capacity to maintain routing information. To cope with this shortcoming, reactive protocols adopt the inverse approach by finding a route to a destination only when needed. However, in reactive protocols, the delay to determine a route would be significantly high and they will typically experience a long delay for discovering a route to a destination prior to the actual communication. Hybrid routing protocols combine the advantages of proactive and reactive routing. The route is initially established with some proactively prospected routes and then serves the demand from additionally activated nodes through reactive flooding.

An example of such protocol is the Zone Routing Protocol (ZRP) [53]. In ZRP, a node proactively maintains routes to destinations within a local neighborhood, which is referred to as a routing zone and is defined as a collection of node whose minimum distance in hops from the node in question is not greater than a parameter referred to as the zone radius. Each node maintains its zone radius and there is an overlap of neighboring zones. The construction of a routing zone requires a node to first know its neighbors, which are discovered by a MAC level Neighbor Discovery Protocol (NDP). The ZRP maintains routing zones through a proactive component called the Intrazone Routing Protocol (IARP) which can be implemented by an existing distance vector scheme. On the other hand, the Interzone Routing Protocol (IERP) is responsible for acquiring routes to destinations that are located beyond the zone radius. The IERP utilizes a query-response mechanism to discover routes on demand. Furthermore, instead of applying a standard flooding algorithm, ZRP exploits the structure of the routing zone through a component called Border Resolution Protocol (BRP).

In summary, there are a lot of routing protocols for mobile ad hoc networks. Our discussion here is far from being exhaustive. Many WMN routing protocols use similar strategies as in MANETs. However, they need to be adapted to the characteristics of WMNs, for example, by using a quality-aware routing metric.

2.3.2 Routing Metrics

Routing protocols process and compute routes with desired properties, for example shortest path or number of hops. Among serval available paths, the best one is selected according to a routing metric. Ad hoc networks usually use hop count as a routing metric. This metric is appropriate for ad hoc networks because new paths must be found rapidly, whereas high-quality routes may not be found in due time. This is important in ad hoc networks because of user mobility. However, the unique characteristics of WMNs impose unique requirements on designing routing metric for mesh networks. In WMNs, the stationary topology benefits quality-aware routing metrics [54].

One popular metric proposed for WMNs is the Expected Transmission count (ETX) [55]. The primary goal of the ETX design is to find paths with high throughput, despite losses. ETX minimizes the expected total number of packet transmissions (including retransmissions) required to successful delivery of a packet to the ultimate destination. To compute ETX, each node periodically broadcasts probes containing the number of received probes from each neighbor. The number of received probes is calculated at the last T time interval in a sliding-window fashion. The derivation of ETX starts with the measurements of the underlying packet loss probability in both the forward and reverse directions because of DATA and ACK transmissions. In addition, ETX also considers the retransmission on the MAC layer. Finally, the path metric is the sum of the ETX values of each link in the path. The selected route is the one with minimum path metric.

Although the ETX metric performs better than shortest path routing, the implementation of ETX has revealed two shortcomings: broadcasts usually are performed at the network basic rate, and probes are smaller than typical data packets. Thus, unless the network is operating at low rates, the performance of ETX becomes low because it neither distinguishes links with different bandwidths nor does it consider data-packet sizes. To cope with these problems, the Expected Transmission Time (ETT) is proposed in [56]. ETT adjusts ETX to different physical layer data rate and data packet sizes. In addition, airtime [6] defined in IEEE 802.11s is a radio-aware metric which is used to measure the amount of consumed channel resources when transmitting a frame over a particular wireless link. Unlike other metrics which count solely frame error rate, airtime accounts for both frame error rate and link date rate. In addition to the metrics considered in ETT, airtime metric further accounts channel access and protocol overheads.

Consecutively, an increasing number of routing metrics have been proposed, such as Metric of Interference and Channel-switching (MIC) [39], modified ETX metric (mETX) [54], interference aware routing metric (iAWARE) [57] and so on. Table 2.1 summarizes the main characteristics of these routing metrics. However, which metric is to adopt depends on network scenario and its requirement.

Table 2.1: Characteristics of Main Routing Metrics.

Metric	Quality-aware	Data rate	Packet size	Intra-flow interference	Inter-flow interference	Medium instability
Hop	×	×	×	×	×	×
ETX	✓	×	×	×	×	×
ETT	✓	✓	✓	×	×	×
Airtime	✓	✓	✓	×	×	×
MIC	✓	✓	✓	✓	✓	×
mETX	✓	✓	✓	×	×	✓
iAWARE	✓	✓	✓	✓	✓	✓

2.4 Load Balancing in Wireless Mesh Networks

As mentioned at the beginning of this chapter, the focus of WMN routing is to improve network performance or the performance of individual transmissions, rather than coping with mobility or energy conservation. Due to the co-existence of many interacting parameters such as network load, link transmission rate, intra-flow and inter-flow interference, and link dynamics, the design of efficient routing in WMNs remains as a topic of interest.

As a basic principle in traditional routing protocols in WMNs, a routing decision is made to find the least-cost path from source to destination, no matter it is based on hop-count or other metrics. However, this is not sufficient to improve network performance due to a few reasons. For instance in shortest path routing, nodes on the shortest path will be more heavily loaded than others as they are more frequently selected as the default routing path. Furthermore, as WMNs are envisaged to serve a large community of users, the average volume of traffic is significantly higher than in a typical mobile ad hoc environment. Since most users in WMNs are primarily interested in accessing the Internet or other commercial servers, the traffic in WMNs is routed either toward the IGWs or from the IGWs to clients. Thus, if multiple mesh routers choose the best throughput path toward the same gateway, the traffic loads on certain paths and mesh routers will increase dramatically, thereafter severely degrading the overall performance of the mesh network.

To improve the performance of WMNs, various approaches can be introduced, from MAC and routing enhancement, to load balancing and cross-layer design. Load balancing is an efficient approach to resolve the congestion problems in WMNs. It can be achieved through path-based load balancing, gateway-based load balancing or mesh router-based load balancing [58]. In path-based load balancing, the traffic is distributed across multiple paths. In gateway-based load balancing, the load is balanced either among all Internet gateways (IGWs) or a few selected gateways [59]. Load balancing can also be carried out at the mesh routers over the wireless backbone. However, traditional routing strategies with load balancing intend to direct all traffic flows *as a whole* to another less loaded path if the ongoing path could not satisfy the requirements [60–62], *without distinguishing the types of services*. These strategies may lead to a potential threat that many traffic flows are suddenly redirected to the same path, causing performance degradation on that specific path.

In Paper A, we propose and investigate the performance of a novel *service-oriented* routing strategies which incorporates both cross-layer design and load balancing. By collaborating across layer design over multiple layers, improved network performance is expected. More specifically, the congestion information derived from layer 2 serves as an indicator to initialize load balancing. Normally, the congestion status of a network is reflected by load metric, referred to as the congestion indicator for the network. For instance:

- *Channel access probability*: This refers to the likelihood of successful access to the wireless medium. It is also related to the degree of channel contention with neighboring nodes;
- *Packets in the queue*: This refers to the total number of packets buffered at both incoming and outgoing wireless interfaces.
- *Active path*: This refers to the number of active paths supported by a node. Generally, the higher the number of active routing paths, the busier the node since it has to help forward more packets.

In the proposed scheme, a combined metric is used to measure the congestion status at each mesh router. Firstly, we focus on the average MAC layer utilization at a node, which reflects the wireless medium around the node is busy or idle. We regard MAC layer utilization as 0 unless the wireless medium is available for a node to transmit a new packet. If there already exists a packet ready to compete for channel access, this utilization condition is defined as 1. Knowing the instantaneous MAC layer utilization at a router as busy or idle, we estimate this value over a certain period to get the average status of the utilization of the wireless medium at an MR. On the other hand we monitor the network interface transmission queue length, which is the number of packets waiting for transmission at the buffer. As the queue become longer, it will increase transmission latency, and even drop packets due to limited buffer size. Combing these two metrics, we will not only get a view of the current condition of the wireless medium but also a prediction of the future load at the MR.

After identifying the congestion status, the load balancing routing scheme is achieved by separating flows into different available paths, according to their traffic types. This method is referred to as *traffic splitting*. Considering distinct traffic features, the performance of two traffic types, User Datagram Protocol (UDP) traffic and Transmission Control Protocol (TCP) traffic, is investigated in our study. Compared with UDP flows, TCP flows are less sensitive with delay, and the end-to-end retransmission mechanism of TCP will guarantee the successful transmission of the traffic.

More specifically, by running the proposed protocol, the gateways broadcast their advertisements with traffic load status periodically, and the mesh routers receive the information. Comparing with the congestion information in each route, the least congested path from MR to the IGW is selected. As for other paths, if the wireless medium around a node is particularly busy that leads to network congestion, the MR would reduce the frequency of forwarding its message until the congestion decreases. In order to reduce the load on this route, it sends a notification to these nodes informing them to look for a new gateway which is relatively less congested. Due to the characteristic of TCP traffic, TCP flows will adjust the window size to fit the congested environment when the network is getting congested or when the network delay increases and packets timed out. As a result of the TCP adjustment itself, it will generate less traffic on the current path. Since UDP could not adjust itself to adapt the congestion situation, it will always try to go through this path even if it is more congested. Considering this feature, in most cases we will switch UDP flow to a less loaded path although the switching would cause certain delay and packet loss. Comparing with the situation when total path is congested, the real time traffic could be delayed and lost, a very short period delay or low packet loss could be tolerated.

We extend OLSR and AODV routing protocols respectively, by considering the traffic splitting policy using the ns2 simulator. It is observed that traffic load is distributed over the entire network, resulting in multifold benefits: (a) excessive congestion inside the network is avoided; (b) the network capacity is optimally utilized; (c) packet loss is decreased and total network throughput increased; (d) greater benefit is achieved for the re-directed traffic flows.

Chapter 3

Cooperative Communications and Relay Selection

3.1 Introduction

Most of the advances in wireless networks are due to practical aspects such as low cost of deployment and support of mobility. However, in the real world, there are disadvantages in wireless communications. Noise and interference in the wireless medium together with signal loss due to path loss and fading may severely reduce the achievable data rate from its theoretical maximum value. Therefore, one of the most important and practical problems in wireless network protocol design is to combat these negative effects in order to achieve higher overall throughput. Cooperation communication is used to assist source-destination pairs that experience poor channel quality to achieve performance improvement via relay nodes.

Cooperative diversity techniques exploit the spatial characteristics of the network to create transmit diversity, in which the same information can be forwarded through multiple paths towards a single destination or a set of destination nodes. The initial attempts for developing cooperative communications concentrated on physical layer techniques [18, 21, 63]. These approaches refer to the collaborative processing and retransmission of the overheard information at the nodes surrounding the source and the destination. By mutually combining different copies of the same signals transmitted by source and relay nodes, the destination can improve its ability to decode the original packets. However, the innovation of cooperative communications is not confined only to the physical layer schemes. To efficiently take the advantage of physical layer information, such mechanisms also require investigation on relaying techniques used for mutually exchanging data, on multiple access methods to schedule the transmission and minimize overhead, on coding schemes used for packets combining and error correcting these packets prior to forwarding, and on the additional scenario factors introduced by cooperation [64]. It is worth noting that if the MAC protocol is not appropriately designed for cooperative communication, the cooperative gain may diminish or even disappear. Therefore, in this chapter, we focus on how physical layer cooperation can influence and be integrated with the MAC layer for higher throughput and more reliable communication instead of only studying the advantages of cooperation at the physical layer.

3.2 Cooperative Communication Protocols in Wireless Networks

3.2.1 Cooperative Relaying Protocol

In cooperative communications, independent paths between nodes are generated via the introduction of relay channels as illustrated in Fig. 3.1. The relay channel can be viewed as an auxiliary channel in addition to the direct channel between the source and destination. A typical cooperation strategy can be divided into two phases:

- In Phase 1, a source node sends information to its destination, and the packet is also received by the relay node at the same time.
- In Phase 2, the relay node can help the source by forwarding or retransmitting the overheard information to the destination[1].

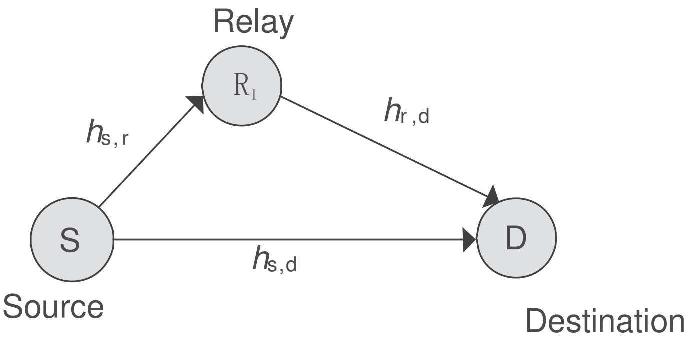

Figure 3.1: A single relay cooperation model

Fig. 3.1 depicts a general relay channel with two transmission phases. In Phase 1, the source node broadcasts the information to both the destination and the relay.

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[1] The source and the relay nodes may also simultaneously transmit different copies of the same packet to achieve diversity gain. It depends on the cooperative diversity algorithm being applied.

The received signals $y_{s,d}$ and $y_{s,r}$ at the destination and the relay, respectively can be expressed as

$$y_{s,d} = \sqrt{P} h_{s,d} x + n_{s,d}, \tag{3.1}$$

$$y_{s,r} = \sqrt{P} h_{s,r} x + n_{s,r}, \tag{3.2}$$

where P is the transmission power at the source, x is the transmitted signal, $h_{s,d}$ and $h_{s,r}$ are the signal attenuation due to propagation in the wireless links from source to destination or relay, respectively. They are modeled as zero-mean, complex Gaussian random variables with variances $\delta_{s,d}^2$ and $\delta_{s,r}^2$, respectively. $n_{s,d}$ and $n_{s,r}$ are additive noise, which are modeled as zero-mean complex Gaussian random variables with variance N_0. $y_{s,d}$ and $y_{s,r}$ are the received signals at the destination and the relay, respectively.

In Phase 2, the relay forwards an original or a processed version of the source's signal to the destination, and this can be written as

$$y_{r,d} = q(y_{s,r}) h_{r,d} + n_{r,d}, \tag{3.3}$$

where function q represents on how the information received from the source node is processed at the relay node. Therefore, a key aspect of the cooperative communication process is how to process the received signal by the relay node. Different processing schemes will result in different cooperative communication schemes. According to the employed processing schemes at the relay node, cooperative relaying protocols mainly fall into two categories: Decode-and-Forward (DF) schemes and Amplify-and-Forward (AF) schemes [65, 66]. While in a DF protocol, the relay node decodes the received signal, re-encodes it and then retransmits it to the destination, the relay node receives the copy of the signal and transmits an amplified version of it to the destination in an AF protocol without modifying the signal. Besides these two common techniques for processing the overheard signal, there are also other techniques, such as compress-and-forward cooperation and coded cooperation, etc.

3.2.2 Cooperative Diversity Algorithms

While cooperative relaying protocols mainly concentrate on signal processing techniques only at the relay node, cooperative diversity algorithms pay attention to both the relay and the source on whether both of them retransmit the packet or not. Therefore, there are two types of cooperative diversity algorithms: *repetition-based* and *space-time-coded* [67]. In the former algorithm, the transmitter broadcasts its transmission both to its receiver and potential relays, and the relays repeat the transmitter's message individually on orthogonal channels (frequency or time). Hence, the two well-known techniques, AF and DF protocols belong to repetition-based cooperative algorithm. The corresponding benefits come at a price of decreased bandwidth efficiency (increased time delay) because each relay requires its own channel (time) for repetition. On the other hand, the space-time-coded cooperative diversity algorithms operate in a similar fashion except that both source and relay(s) transmit simultaneously on the same channel using a suitable coding scheme such as orthogonal Distributed Space-Time Code (DSTC). For realizing cooperative diversity while allowing relays to transmit on the same channel, orthogonal DSTC has been studied [67, 68]. Historically, Space-Time Coding (STC) and Space-Time Block Coding (STBC) were initially developed to offer transmit diversity in multi-antenna systems [9]. In other words, multiple copies of a data stream are encoded based on the space-time code and transmitted through multiple antennas to improve the reliability of data transfer. STBC has been a dominant algorithm for both Multiple Input Single Output (MISO) and Multiple Input Multiple Output (MIMO) system architectures because maximum likelihood decoding can be accomplished with only linear processing at the receiver while achieving full diversity.

Recently, there has been active research in developing cooperative MAC protocols based on these two algorithms. For instance, CoopMAC [69] is a cooperative protocol for infrastructure wireless LANs, which aims to support and improve the communication of wireless stations with the help of cooperative communication. In such a case, a relay station located somewhere between the transmitter and the receiver, is used to boost data communication efficiency. More specifically, the transmitter, instead of sending its packets directly to the receiver at a low daterate, uses the relay to transmit the packets in two high daterate hops, thus decreasing transmission time. In this way, the particular communication lasts less time, resulting in not only the improvement of the throughput but also the increase of spatial reuse, in the sense that neighboring stations can initiate a new transmission earlier than they otherwise would have. On the other hand, CD-MAC [70] allows the transmitter to proactively select a relay for cooperation and lets the source and the relay transmit simultaneously when it is beneficial in mitigating interference from nearby transmitters and thus improving network performance. To address both types, in the composition of this dissertation, Paper E addresses space-time-coded cooperative diversity while other cooperation related papers, B, C and D work on repetition-based cooperative diversity. From the concept of cooperation and these examples, we find that it is important to select the most appropriate relay(s) to perform communication.

In Papers B-E, different relay selection algorithms according to different scenarios have been studied as part of the cooperative MAC design. In the following sections, we will summarize relay section schemes including optimal relay selection, optimal number of relays, relay selection process and retransmission strategy.

3.3 Optimal Relay Selection

Relay selection is an essential procedure for cooperative communications. A relay can be selected according to its instantaneous channel gains on the basis of a real-valued metric that is a function of the relay-destination channel gain, the source-relay channel gain, or both. An illustration of network model for relay selection is shown in Fig. 3.2.

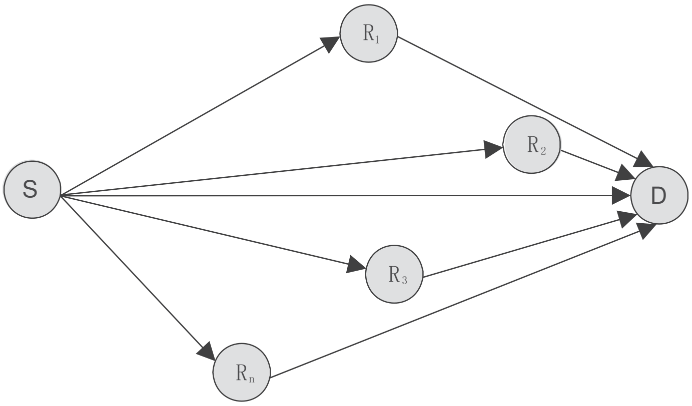

Figure 3.2: Network model for relay selection.

3.3.1 Best Relay Selection

There exist a rich body of literature on relay selection [44, 71–78]. Normally in a relay selection algorithm, the source node monitors its neighbors and dynamically determines a relay as the one which exhibits the best link quality. This is the optimal single relay selection scheme. The error rate of this scheme is first discussed in [79], in which an approximation on the cumulative density function of the received SNR is used. Then, a rigorous upper bound on the error rate of this scheme is given in [80]. In [77, 81], the nearest neighbor selection is proposed, in which the relay that is the closest to the destination cooperates. In those two papers, DF is used and node spatial positions are considered. Although this selection criterion might not be optimal in all scenarios, it is very simple to be implemented in a distributed manner and can achieve high performance, as demonstrated in [81].

3.3.2 Best Worse Channel Selection

Since there are a pair of links along the source-relay-destination path as the source-relay channel and the relay-destination channel, how to decide the best link is not trivial. In the literature, many researchers prefer to consider only the relay-destination channel, by assuming that the source-relay channel is perfect. This assumption may not be precise since the cooperative benefits from relay nodes usually depend on both channels. If one of the channels corrupts, the relay cannot successfully forward the packet. Therefore, in Papers B and D, we select the optimal relay according to a combined link quality indicator which takes both two channels into consideration. Among all relay nodes, the one whose worse channel has the best link quality will be selected as the optimal relay. That is,

$$SNR_{opt} \Leftrightarrow max\{SNR_i\}, i \in [1,n] \Leftrightarrow max\{min\{SNR_{si}, SNR_{id}\}\}, i \in [1,n], \quad (3.4)$$

where n is the number of relays available for the source-destination pair; SNR_{si} and SNR_{id} are the link conditions in terms of received SNR from the source to the relay and from the relay to the destination respectively. Relay i with maximal SNR_i is the optimal one. This scheme is able to balance the signal strength of these two links. The diversity multiplexing tradeoff of this scheme is analyzed in [78].

3.4 Optimal Number of Relays

While most of relay selection schemes focus on a single relay selection, i. e., only one of the relay nodes cooperates, another alternative is to use multiple relay nodes so that both spatial diversity and time diversity can be obtained since relay nodes are spatially distributed. In Paper B, it is demonstrated that with proper design of cooperative multiple access control protocol, multiple relay strategy outperforms single relay scheme. For networks with a large number of relay nodes, say n, as each relay has two choices, there will be $2^n - 1$ possibilities of cooperations (the case that no relay cooperates is obviously excluded). Even though the destination node knows all the channels so that it could find the optimal solution by exhaustive search, the computational complexity of this exhaustive search is expensive. Thus, a critical task for multiple relay selection schemes is to find an optimal number of relay nodes with low complexity and excellent performance.

In Paper B, relay nodes forward the copy of the overheard packet in different time slots. Instead of retransmitting the packet by one relay node, the protocol allows multiple relays to transmit the copy of the original packet until the destination could successfully receive the packet. However, the number of transmissions (i.e., the optimal number of relays) is determined on the fly rather than pre-defined by any node. In [82], the authors derive the optimal number of retransmissions for certain channel in order to successfully receive the packet by the destination node. Note that with each specific channel condition, there will be an optimal number of relays which maximizes system performance. Similarly, in the case that a number of relay nodes are around the vicinity of both the source node and the destination node, we could derive an approximation of the number of optimal relay nodes in the similar way as the number of retransmissions. It is suggested that the best size of the cooperation group is around $\frac{1}{(1-P_{si})(1-P_{id})}$, where P_{si} is denoted as the probability of unsuccessful packet transmission in the primary channel between the source and the relay nodes, approximatively taken as Packet Error Rate (PER), and P_{id} is the PER for the relay channel between the relay and the destination. Since $\frac{1}{(1-P_{si})(1-P_{id})}$ is not a whole number in general, the optimal cooperation group size will be rounded to an integer.

Given the assumption in the network that all channels are independent and identically distributed (i.i.d.), the received link quality is different from path to path among various relays. If channels exhibit high quality, then fewer relays are required, and vice versa. Considering the fact that each relay experiences different channel condition resulting in a different number of required relays and that a large number of relay nodes may decrease transmission efficiency, we define the optimal number of relays according the relay candidate which provides the *best combined channel link quality* (see in Eq. (3.4)) as

$$Optimal\ number\ of\ relays = min\lceil \frac{1}{(1-P_{si})(1-P_{id})} \rceil, \ \ \forall i = (1, \dots, n). \tag{3.5}$$

In Paper E, Cooperative Transmission (CT) in the MAC design forms a virtual MISO transmission, which has been demonstrated to be able to extend the transmission range [83]. In MISO techniques, range extension mainly depends on the number of cooperators, N_c, in which the diversity gain is derived from. Thus, the main objective of the multiple relay selection scheme is to choose N_c. As concluded in [83], cooperative diversity gain is monotonically increasing with N_c. On the other hand, we do not want N_c to be unnecessarily large, because it will result in noticeably high total energy consumption for performing CT. Therefore, it is necessary to obtain an approximation of the number of cooperators on the basis of range extension factor. The range extension factor, β, is defined as the ratio between the cooperative transmission distance, d_{ct}, and the SISO link distance, d_{non-ct}, i.e., $\beta = d_{ct}/d_{non-ct}$. For Rayleigh fading, β is given as [83],

$$\beta = 10^{(10log_{10}N_c + G(N_c))/10\alpha}, \tag{3.6}$$

where N_c is the number of cooperators, $G(N_c)$ is the cooperative diversity gain by N_c number of cooperators, α is the path-loss exponent, which is typically between 2 and 4. In the proposed algorithm, given the extension factor β we could obtain the approximation of N_c. Table I provides a few examples of the relations between N_c and β at a target Bit Error Rate (BER) of 10^{-3} [83, 84].

Table 3.1: Diversity Gain and Range Extension (BPSK. BER=10^{-3}).

N_c	2	3	4	5	10
$G(N_c)(dB)$	10	13.5	14	14.5	15.9
$\beta(\alpha = 3)$	2.71	4.07	4.65	5.2	7.3

3.5 Relay Selection Process

In most of the literature, the studies address only the problem of ”whom to cooperate with?”, but few investigate the procedure of ”how to carry out this process?”, especially in a distributed environment. Generally speaking, whether or not the relay selection algorithm could provide maximum benefits depends not only on the optimal relay but also on how it is implemented. For instance, in a MAC scheme, if the selection process costs too much control packet exchange to select the optimal relay, cooperation gain may be compromised due to such overhead.

After the relay nodes receive the data packet derived from the source node, the cooperation protocol typically uses two phases to complete the transmission to the destination: (i) a relay selection phase, in which the best relay is chosen by a selection mechanism, and (ii) a data transmission phase, in which the data is forwarded to the destination by the selected relay. Although the protocol needs to spend time and energy in the selection phase, it could benefit the system, in the way of increased throughput or lower energy consumption, during the data transmission phase. However, in [85, 86], the authors model several practical aspects of a contention-based selection process, in which the simulation results show that the relative fraction of time and energy spent in the relay selection phase is not negligible. For example, in a centralized polling mechanism, the time for selection increases linearly with the number of available relays. The overhead of selection phase can be reduced by using distributed mechanisms based on back-off timers [78].

In Paper D which considers a TDMA-enabled WMN, we employ a distributed timer-based relay selection process. Each relay node sets its own timer T_i such that the timer of the node with largest SNR_i expires first. Correspondingly, the node whose timer expires first will transmit its packet first if there are multiple relay nodes.

$$T_i = \frac{SNR_{threshold}}{SNR_i} m T_{ms}, \tag{3.7}$$

where $SNR_{threshold}$ is the SNR threshold to guarantee that the channel is in good condition. Only relays with $SNR_i \geq SNR_{threshold}$ are qualified as the candidate for optimal relay. T_{ms} is the time duration of one mini-slot, m is the number of mini-slots. It means that the timer of the eligible relay should expire within the specific time interval in order to avoid long delay.

It is worth noting that the selection process may not always find the best relay. For example, the system may terminate the selection phase after a pre-determined time even if the best relay has not been selected. This leads to transmission error during the subsequent data transmission phase. While increasing the selection phase duration reduces this error probability, it does so at the expense of the overall system throughput since a smaller fraction of time is used for data transmission. Doing so also increases the energy consumed in the relay selection phase. Thus, these two phases affect each other, and cannot be optimized in isolation. However, in Paper D, we fulfill the relay selection phase within the inherent time of the system, i.e. control mini-slot time. It means that this time will be consumed no matter the selection process is performed or not. In other words, the fraction of the selection phase is fixed, which is the smallest ratio between the control part and the data part of a frame. More details could be found in the medium access control part in the next chapter.

Another advantage of the timer-based relay selection scheme is to provide short delay, as demonstrated in Paper E. From channel access point of view in the MAC design, any node could be selected as the first one to access the channel if there are multiple nodes at present. Occasionally, it is preferred that some of the nodes have priority for channel access because of the QoS requirement. For instance, in energy constraint WSNs, the willingness of the node with highest residual energy to do cooperation is much higher than those nodes with less energy. Therefore, with the timer-based node selection scheme as shown below, we could select the node with highest remaining energy as the cooperator.

$$T_i = \lfloor (1 - \frac{V_i}{V_{max}})\Delta \rfloor, \tag{3.8}$$

where V_i represents the residual energy of node i, V_{max} is the maximum of V_i, and $\lfloor \cdot \rfloor$ is the floor function. It is shown that nodes will transmit only at finite discrete time instants. The granularity of T_i could be configured flexibly. However, if the T_i values are too close to each other, the DATA message may also collide. On the other hand, if each T_i value is too far away from each other, it will result in long delay. Here, we determine the granularity of T_i based on Δ. We turn Δ depending on an acceptable value of the collision probability [87].

Chapter 4

Cooperative MAC Design in Multi-hop Wireless Networks

4.1 Introduction

Cooperative communications have been proved to be able to improve system performance from the physical layer perspective. For efficient cooperative communication, operations at the physical layer should be coupled with those at higher layers of the protocol stack, in particular with the MAC layer. While fairly extensive research has been carried out for the physical layer of cooperative communication networks, the research focus is tending to move to MAC design of cooperative protocol recently. MAC protocol, which is conventionally viewed as part of the Data Link Layer in the OSI model, coordinates the use of a shared wireless medium in multi-user systems and ensure fair access for end users. Due to limited bandwidth, fast-varying channels and energy-costly transmissions in wireless systems, it is particularly important to derive MAC protocols that efficiently utilize channel resources. Hereby the design goals of a cooperative MAC protocol include:

- The access delay, represented by the average delay experienced by any packet to get transmitted, should be kept low.
- The available bandwidth should be utilized efficiently.
- The protocol should ensure fair allocation of bandwidth to all nodes.
- The control overhead should be kept as low as possible.
- The protocol should minimize the effects of hidden and exposed terminal problems.

- The protocol should be scalable to large-scale or medium-size networks.

In this chapter, we will introduce the traditional medium access control protocols and cooperative MAC design in different categories of MAC protocols. In addition, we investigate how to extend cooperation benefits into multi-hop wireless networks as well as how to perform cooperation in a duty cycle enabled wireless sensor network.

4.2 Medium Access Control Protocols

4.2.1 Traditional MAC Protocols

MAC protocols have been studied extensively for many years, ranging from wireline telephony networks to the Internet, and to wireless ad hoc networks. The efficiency of the MAC protocol design is crucial for wireless networks due to limited bandwidth resources. MAC protocols are mainly divided into two categories: distributed MAC protocols and centralized MAC protocols, based on whether or not a control center is available for medium channel access. In a distributed wireless network, based on the fact that the users in the system are independently transmitting data and they are competing for channel access, MAC design has to pay special attention to collision avoidance. This is typically achieved through either *random access* or *scheduling*. In this section, we will briefly introduce a few traditional MAC protocols as examples for these two types of approaches.

The Carrier Sense Multiple Access (CSMA) [88] protocol is the most popular and primitive choice for random access networks because of its simple and effective design. In this protocol, a node first senses the channel to determinate whether there are ongoing transmissions before sending its packet. Sensing the carrier and accessing the medium only if the carrier is idle decrease the probability of collision. However, hidden terminals cannot be detected. If a hidden terminal transmits at the same time as another sender, collision may happen at the receiver.

There exist serval versions of CSMA protocol, such as non-persistent CSMA and p-persistent CSMA. In the former protocol, stations sense the channel and start sending immediately if the medium is idle. If the medium is sensed as busy prior transmission, the transmission is deferred for a random interval before sensing the medium again. The same procedure is repeated for the next transmission attempt. This reduces the probability of collisions on the channel. In p-persistent CSMA, nodes also sense the channel, but only transmit with a probability of p after the channel has been sensed as idle, and the station defers its transmission to the next slot with the probability $1 - p$.

In addition, to provide fair access for competing stations, a backoff algorithm is introduced, which is applied in CSMA with Collision Avoidance (CSMA/CA). CSMA/CA is a modification of CSMA with the goals of providing reliable transmission, fair access and protection of ongoing traffic.

The IEEE 802.11 MAC protocol specifies a Distributed Coordination Function (DCF) which adopts the Request-To-Send (RTS)/Clear-To-Send (CTS) message exchange for unicast data transmissions. DCF employs CSMA/CA with binary exponential backoff algorithm. When a node intends to transmit a message, it will first sense whether other node is already transmitting. If no other transmissions are sensed, the node will send a small RTS packet to its intended recipient. If the recipient senses that the medium is free, it sends a CTS packet in reply. Once the node wishing to transmit receives the CTS packet, it sends the actual data packet to its intended recipient. If the transmitting node does not receive a CTS packet in reply, it begins the RTS procedure over again. If the node does sense another transmission when it is ready to send, it will apply a binary exponential backoff timer. After the timer has expired it will start sampling the medium again to see if it can start transmitting.

As opposed to CSMA, TDMA provides each node with interference-free channels through deterministic scheduling. Specifically, TDMA divides the use of the channel into fixed time slots and schedules the transmission of each node among these time slots based on their service demands and total available resources. TDMA requires strict synchronization among nodes in order to coordinate the use of the channels. Benefitting from the coordination, it is easier for TDMA to satisfy users' QoS demands, e.g., delay or Bit-Error-Rate (BER) requirements, with less protocol overhead. Additionally, the coordination also allows TDMA to achieve higher throughput under heavy traffic loads.

4.2.2 Cooperative MAC Protocols

Both CSMA and TDMA protocols have been used as a basis for many wireless MAC protocols. For instance, as introduced in Chapter 3, CoopMAC is developed based upon the IEEE 802.11 distributed coordination function mode. Persistent RCSMA [89] is claimed to be the first MAC designed to execute distributed cooperative automatic retransmission request scheme in wireless networks. In persistent RCSMA, all stations are invited to become active relays as long as they meet certain relay selection criteria. Then the qualified relay nodes will attempt to access the channel according to the DCF protocol. Additionally, Cooperative Relaying

Medium Access protocol (CoRe-MAC) [90] proposes a novel cooperative MAC protocol which extends the standard CSMA/CA protocol to increase reliability and throughput of the wireless communications.

Although a few studies on cooperation-based MAC protocols have been performed, there are still many open questions in this research area. In the following sections, we will further introduce how cooperative communications are efficiently implemented in different categories of MAC protocols.

4.3 Cooperative MAC Protocol in Multi-hop Wireless Networks

4.3.1 A Contention-based Cooperative MAC Protocol

Most of existing cooperative MAC protocols are designed based on random access control, which is suitable for wireless LAN and wireless ad hoc networks. In Paper B, we have proposed a contention-based multiple access protocol for cooperative wireless networks. While most of the cooperative MAC protocols focus on one widely-used model in which a pair of source-destination nodes and a single relay form a triangle transmission scenario, we use multiple relay nodes to do cooperation so that both spatial and time diversity can be obtained since relay nodes are spatially distributed.

The system model has been shown in Fig. 3.2, which consists of a source node, S, a destination node, D, and n intermediate relay nodes between nodes S and D. Since all relay nodes may attempt to access the common channel at the same time, it is necessary to design an efficient medium access protocol to avoid collision among competing relay nodes. In the proposed scheme, when the direct transmission from S to D fails, instead of asking only the optimal relay specified by the relay selection criterion to retransmit via the error-prone channel until the destination correctly receives the packet, we use different relay nodes that overhear the original packet transmission to retransmit over diverse paths. Although the optimal relay selection is able to provide the best relay for cooperation, our scheme allows selected relays to forward the packet, eliminating the requirement on selecting exactly the most appropriate relay.

The timing diagram of the MAC mechanism is illustrated in Fig. 4.1. Briefly, node D initiates the cooperation by broadcasting a Call For Cooperation (CFC) packet when it fails receiving a packet. Upon receiving the CFC packet, all relay nodes will compete for channel access to forward the overheard packet. Each node performs a back-off procedure with only one stage, which means that the retry limit is set as one. If the retransmission fails, then all nodes start to compete for channel access. Furthermore, node D will keep the received copies of the original packet from different relay nodes until the number of copies reaches the optimal number of required packets to decode successfully. The optimal number could be derived in a similar way as specified in Eq. (3.5).

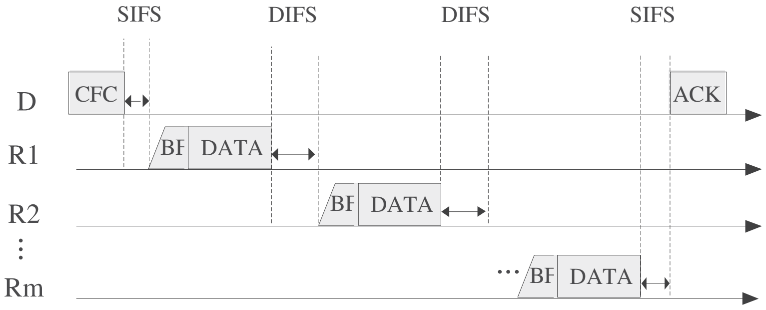

Figure 4.1: Contention-based cooperative MAC protocol.

A Markov chain model characterizing the network operation is built for our performance analysis. Numerical results demonstrate that by using the proposed scheme overall system throughput can be significantly improved under different channel conditions.

4.3.2 Cooperative MAC Design: When Source and Destination are Two-hop Away from Each Other

While the cooperative MAC protocols in a single hop wireless network have been well studied in a number of publications, e.g., [69], their applicability to multi-hop network performance is not yet well investigated. As an effort towards cooperative communication in multi-hop wireless networks, in Paper C we propose a Two-hop Cooperative MAC protocol (TC-MAC) specifically designed for two-hop communications. A salient distinction between this work and existing cooperative MAC protocols [69, 70, 91] is that in our scenario the source node and the destination node cannot hear each other, i.e., no direct communication between source and destination is possible. In other words, the communication between source and destination has to be forwarded via relay nodes which are one-hop neighbors of both source and destination. The system model is illustrated in Fig. 4.2.

To make our TC-MAC scheme work, a key element is relay selection. Although relay selection has been addressed by many publications [78, 92] as a means to im-

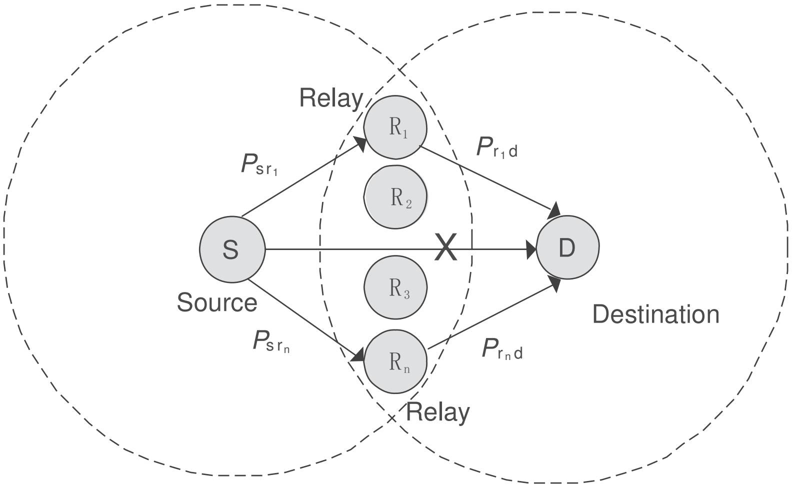

Figure 4.2: System model for two-hop cooperative communications

prove reliability in wireless communication systems, they are not targeted at two-hop communications. The relay selection procedure in TC-MAC includes identifying a set of multiple relay nodes which are qualified to forward the received information toward the destination and a method to select the most appropriate relay(s) to forward information. While in most of existing work each node monitors its neighborhood and determines a single node with best link quality as the relay node, solely based on link information of either the first hop or the second hop, we dynamically select a set of nodes according to both links from the source to the relay and from the relay to the destination, as described in Section 3.3.2.

Based on the combined link quality relay selection scheme, we further propose a concept referred to as Multiple Relay Points (MRPs). Inspired by the concept of MPR defined in OLSR [45] in which a one-hop neighbor is selected to forward packets to as many as possible two-hop neighbors, we employ MRP in which one or more one-hop neighbors are selected as relays to forward packet to the same two-hop destination. While the purpose of using MPR is to reduce overhead for routing message broadcast in ad hoc networks, the idea of introducing MRP is to achieve spatial diversity in multi-hop cooperative wireless networks through multipath transmissions by MRP nodes. As an example, if there exist multiple nodes which are one-hop neighbors of both the source and the destination nodes, only a selected number of potential relay nodes which satisfy the relay selection criterion belong to the forwarding set, MRP. When the adaptive TC-MAC scheme is employed, the number of required MRPs can be dynamically adjusted according to combined two-hop channel conditions. For example, as channel condition deteriorates, more MRPs are selected in order to provide higher spatial diversity gain.

If there is only one MRP required, the TC-MAC protocol works similar to the original 802.11 DCF scheme when used in the two-hop case, except that the random back-off mechanism in the second hop is replaced by a scheduled transmission from the relay node in our case. The timing diagram of the adaptive TC-MAC by using two MRPs as an illustration is shown in Fig. 4.3. In brief, the adaptive TC-MAC works as follow: 1) Obtain individual channel quality for both one-hop and two-hop links, and establish a neighbor and link database; 2) Calculate the overall two-hop combined link quality; 3) The source node decides how many MRPs will be employed for the next transmission cycle as well as their transmission order; 4) The frame transmission sequence follows what is shown in Fig. 4.3; 5) For each new cooperative transmission cycle, go to Step 1), no matter the previous cycle is successful or not.

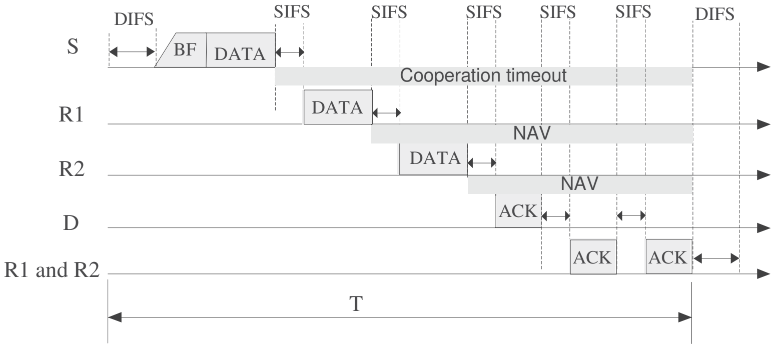

Figure 4.3: Cooperative scheme by two MRPs.

4.4 A TDMA-based Cooperative MAC Protocol

Although there exist many cooperation-based MAC protocols, e. g., [69, 70], for 802.11 networks, very little work has been done on how to enable cooperative communications in TDMA-based multi-hop networks. It is known that when a traditional CSMA-based MAC protocol is applied, the performance will deteriorate in a multi-hop network due to its intrinsic MAC design principle. On the other hand, TDMA system has demonstrated its efficiency, especially in WMNs with static topology. That is, TDMA can conquer those problems that CSMA-based MAC mechanisms suffer from, e.g., packet collision and hidden terminal problem, since it schedules transmission time instances of neighboring nodes to occur at different time slots. However, there are still problems to apply TDMA into multi-hop wireless networks, such as synchronization, and efficient time slot allocation. While synchronization can be provided by a Global Positioning System (GPS) based solution, how to efficiently schedule each transmission at different time slots for cooperative transmissions still remains as an open question.

In [93], the authors propose a multiple access approach based on an idea in which the relay node utilizes the empty time slot available in a TMDA frame to launch cooperation. Although this method improves packet retransmissions when idle time slots are available, it becomes less effective when traffic load is high, i.e., when few idle slots are available. C-TDMA [94] attempts to handle this problem in a way that by using its own time slot neighbour nodes help the source node to retransmit the unsuccessful packets. However, due to the sacrifice of its own time slot the neighbor node may confront a situation that no slot is available for its own packet transmission. Therefore, this method will bring unfair transmission into the network which may affect aggregate throughput from a multi-hop point of view.

In Paper D, we propose a novel TDMA-based cooperative protocol in wireless mesh networks. The proposed MAC protocol makes use of control mini-slot to dynamically and efficiently allocate channel resource not only for direct transmission but also for cooperative transmission. Furthermore, access priority is always given to cooperative transmission through an optimal relay node determined by a timer-based relay selection algorithm as introduced in Section 3.5.

4.5 Cooperative MAC Protocol for Wireless Sensor Networks

Another type of multi-hop wireless networks is wireless sensor networks, which are appealing to researchers because of their wide range of application potential in areas such as environmental monitoring, industrial process monitoring, and target detection etc. Various medium access control protocols with different objectives have been proposed for WSNs. While traditional MAC protocols are designed to maximize system throughput, minimize latency, and fully utilize bandwidth resource, the most important distinct between WMNs and WSNs is that WSN MAC protocol design must be energy efficient since it is impractical to recharge to recharge or replace the exhausted battery of the sensor nodes. On the other hand, compared with other wireless networks, fairness among sensor nodes is usually not a design goal, since nodes in a wireless sensor network are typically part of single application and share a common task.

4.5.1 Duty Cycle MAC Protocol

Distinguished from MANETs, wireless sensor networks have their own inherent characteristics that need to be addressed for their MAC design. There are several reasons that a traditional MAC protocol may have negative impact when applied in wireless sensor networks, including:

- Collisions: If two nodes transmit at the same time and interfere with each others' transmissions, packets will be discarded. Hence, the energy used during transmission and reception is wasted. Also the overhead of the RTS/CTS handshake to implement collision avoidance is considered as prohibitive in comparison with the small WSN payloads, leaving the hidden-terminal problem un-solved. The usual cure of retransmitting messages may actually degrade performance because that the additional traffic causes more collisions, in turn triggering even more retransmissions, and cascading into total collapse in the worst case.

- Overhearing: As radio channel is a shared medium, a node may receive packets which are not intended to it. This reception is simply a waste of energy, and becomes problematic in dense networks with many nodes inside the reception range of a node.

- Protocol overhead: MAC headers and control messages are considered as overhead because they do not contain useful application data, yet consume energy. In the case of WLAN traffic these costs can be amortized, but the small WSN payloads are beyond the boundary considerably, which essentially rules out sophisticated protocols that exchange detailed information.

- Traffic fluctuations: traffic generated by WSN applications often fluctuates in time (event-based reporting) and in place (convergecast) [95]. The resulting peak loads may drive the network into congestion, or alternatively enforce the use of long contention window. In either case, energy consumption rises to undesired levels.

- Idle listening: It happens in such a case that a receiver is waiting to receive anticipated traffic which is never sent. If nothing is sensed during these time periods, sensor nodes have to be in idle mode for most of the time.

It is revealed that one of the largest sources of energy consumption in wireless sensor nodes is idle listening [96]. Duty cycle MAC has been proposed as an effective approach to reduce this problem so as to prolong the lifetime of wireless sensor networks, in which sensor nodes alternate between being active and sleeping. When being active, a node is able to transmit or receive packet, whereas when being sleeping, the node turns off its radio to save energy. In the literature, duty cycle MAC protocols roughly fall into two categories: synchronous and asynchronous protocols. Synchronous approaches, such as S-MAC [23], DW-MAC [20], and T-MAC[7], synchronize neighboring nodes in order to align their active or sleeping periods. Neighbor nodes start exchanging packets only within the common active time, enabling a node to sleep for most of the time within an operational cycle without missing any incoming packet. This approach greatly reduces idle listening time, but the required synchronization introduces extra overhead and complexity, and a node may need to wake up multiple times if its neighbors are on different schedules. On the other hand, in asynchronous duty cycle MAC protocols, such as B-MAC, RI-MAC, and WiseMAC, each node sleeps and wakes up independently according to its own schedule. Such protocols typically employing Low Power Listening (LPL), in which, prior to data transmission, a sender transmits a preamble lasting at least as long as the sleep period of the receiver. When the receiver wakes up and detects the preamble, it stays awake to receive the data. These protocols achieve high energy efficiency and remove the synchronization overhead required in synchronous duty cycle approaches. However, they are mainly designed for light traffic, and it is found that they become less efficient in latency, power efficiency, and packet delivery ratio as traffic load increases, due to their long preamble transmissions. Generally speaking, which protocol is more applicable mainly depends on the network and application requirements.

Considering that duty cycle MAC protocol could reduce the energy consumption of each node in wireless sensor networks and cooperative MAC protocol could prolong the lifetime of the energy-depleting nodes, it would be promising to integrate cooperation into duty cycle MAC protocols. However, cooperative transmission works only if there are multiple active sending nodes, which could help each other relay packets. In the rest of this section, we will present cooperative communications in asynchronous and synchronous duty cycle MAC protocols respectively.

4.5.2 Cooperation in Asynchronous Duty Cycle MAC Protocol

OC-MAC [97] proposes an asynchronous duty cycle MAC protocol which could reduce idle listening and save energy by exploiting cooperative communication among active sending nodes. In OC-MAC, active neighboring senders are permitted to exchange data with each other aggressively when waiting for receivers to wake up. After delegating data to another sender, a sender can go to sleep before its receiver wakes up. Briefly, between a pair of active senders as shown in Fig. 4.4, a handshaking mechanism similar to RTS/CTS is used to establish the cooperation relationship. After receiving a Ready To Receive (RTR) message from a contender, a sender compares its residual energy with this contender. If it has more residual energy, it starts a back-off timer to contend for broadcasting a Clear To Receive (CTR) packet. Otherwise, it also backs off a period but then broadcasts its own RTR packet to contend for transmitting its data first. Once a sender receives a CTR message, which is the reply to the RTR it broadcasts, a sender begins to transmit its DATA to the selected relay. In this way, the protocol could guarantee that the active sender with lower energy could transmit its packet first and then this node could go to sleep. Therefore, it helps reduce idle listening for sending nodes to save energy.

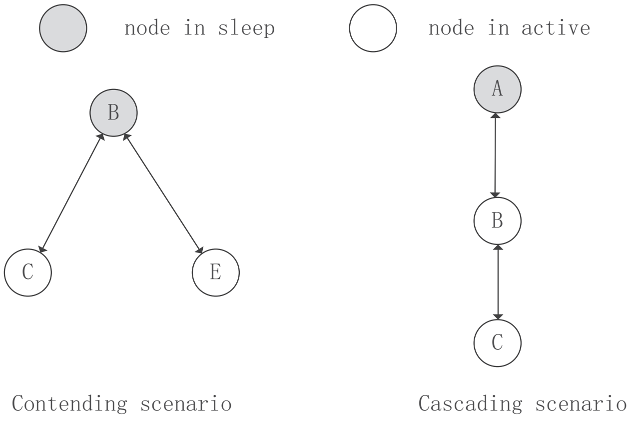

Figure 4.4: Network models for OC-MAC.

However, in OC-MAC, cooperative communication could last until there is no active sender in the neighborhood or the receiver wakes up. In general, the duty cycle which is the fraction of time that a system is in an ”active” state, is expected to be designed as a low value in WSNs. Thus, when OC-MAC is performed based on an asynchronous MAC protocol, in which each node follows its own schedule independently in a low duty cycle, the likelihood that two and even more senders keep active in the same time interval is very small. It means that cooperation communication in OC-MAC occurs with a pretty lower probability. Consequently, the energy conservation will also be limited. On the other hand, OC-MAC takes advantage of cooperation between multiple active sending nodes, in which a sender with lower energy requires another sender with higher energy to relay its packet. In other words, senders only forward packets instead of addressing any cooperative diversity gain from the physical layer, for instance, in terms of SNR advantage. This will lead to a limited benefit from cooperative communication.

4.5.3 Cooperation in Synchronous Duty Cycle MAC Protocol

In Paper E, we propose a novel cooperative duty cycle MAC protocol with multiple wake-ups in wireless sensor networks, referred to as CDC-MAC. CDC-MAC balances the energy distribution in the network by exploiting cooperative diversity gain. While OC-MAC is an asynchronous MAC protocol, CDC-MAC works as a synchronous MAC protocol in which multiple nodes are allowed to exchange data and cooperation information with each other at the same wake-up time interval. To the best of our knowledge, there is no previous work on synchronous duty cycle MAC protocol in networks that also does cooperative transmission.

In WSNs, the data collected from sensors is usually gathered and forwarded to a single or multiple nodes (sinks), which is considered to have no energy constraint and unlimited resources. In a multi-hop environment, this many-to-one wireless network is known to pose a so-called energy hole problem, which can be described as the situation when the nodes around the sink consume relatively more energy and die early, causing the rest of the network to become disconnected from the sink. To keep the network alive, one solution is to perform transmission with longer distance which could jump over the energy hole and reach the two-hop away node directly. Transmission range extension could be achieved through cooperative transmission by forming a virtual MISO transmission. Nodes in the same vicinity instantaneously transmit and/or jointly receive appropriately encoded packets could generate cooperative diversity, enabling a significant Signal-to-Noise Ratio (SNR) advantage in a multi-path fading environment. With this advantage, an increased transmission range could be obtained, resulting in balanced power consumption among nodes. However, to perform cooperative transmission in a duty cycle WSN, it is necessary to ensure that the corresponding nodes are active at the same time interval to transmit data. In this case, synchronous duty cycle protocol is a good option since nodes could be synchronized to wake up at the same time period. After delegating data to another sender, multiple senders do cooperative transmission to hop over the highly-burdened energy-bottleneck node. In this way, the energy-bottleneck node could avoid depleting early so that the network lifetime is prolonged.

Chapter 5

Summary of the Included Papers

5.1 Summary of Paper A

Novel Traffic Splitting Policy for Performance Improvement in Wireless Mesh Networks

Problem Statement

Wireless mesh networks are gaining lots of popularity owing to their increased application to community and public safety networks. WMNs form a static wireless backhaul to provide connectivity to both fixed and mobile clients. The wireless medium, being shared and contended for, creates a number of hurdles, such as collision and congestion. Congestion in WMNs will lead to long transmission delays, packet loss, bandwidth degradation, and waste time and energy on congestion recovery.

Summary

Paper A proposes a service-oriented routing scheme to cope with network congestion, which directs different paths for different service types, according to network congestion status. The protocol responds quickly to changes in network conditions and satisfies with load balancing for different categories of traffic. Since the capacity of a routing path may not be sufficient for all types of traffic that the network has to deliver, it is necessary to route packets to different paths in order to achieve satisfactory performance according to their service requirements. Considering distinct traffic features the performance of two traffic types, UDP and TCP traffic, are investigated in the study.

In addition, in order to achieve load balancing in WMNs, the path selection from a mesh router toward to a gateway has to rely on specific routing metrics. Briefly, the proposed scheme works as follows: use hop-count based routing when traffic load is light, and re-direct certain traffic types to a less congested gateway when traffic load is heavy. Here, potential congestion at gateway node is monitored based on the average MAC layer utilization and the average queue length estimated over a specified time period. Considering these two features, we will gain insight into not only the current condition of the wireless medium but also a prediction of the future load at the mesh router. In order to evaluate the proposed traffic splitting policy, extensive ns2 simulations are conducted. Throughput for each traffic flow and packet loss ratio at mesh routers are used as performance measurement.

Main Contribution

The main contribution of this paper is a cross layer congestion-aware routing scheme, which could efficiently enhance system performance. The results in Paper A illustrate that the proposed scheme could moderately reduce packet loss and significantly increase aggregate network throughput in comparison with the legacy routing protocol. Especially, the split traffic achieves great benefit with the aid of better utilizing the resources in the whole network.

Related Work

Multi-path routing protocols can be used to provide load balancing in wireless mesh networks in the way that each node maintains multiple paths from itself to the Internet gateway. The method proposed in [98] could support multi-path routing naturally. Split Multi-path Routing (SMR) proposed in [99] focused on building and maintaining multiple paths for traffic splitting with consideration of maximally disjointedness between these paths. Furthermore, TCP performance degradation over SMR is investigated in [100]. Another random congestion control scheme which used Markov chain to predict congestion and consequently reduced protocol overhead using longer dissemination intervals was proposed in [101]. However, none of these efforts considerers traffic splitting as part of a routing protocol under heavy network load or when congestion happens in WMNs, which is the main motivation of this paper.

5.2 Summary of Paper B

A Contention-based Multiple Access Protocol in Cooperative Wireless Networks

Problem Statement

In wireless networks, wireless channels suffer from fading, meaning the signal attenuation can vary significantly over the course of a given transmission. Transmitting independent copies of the signal generates diversity and can effectively combat the deleterious effects of fading. In particular, spatial diversity is generated by transmitting signals from different locations, thus allowing independently faded versions of the signal to be jointly decoded at the receiver. The broadcast nature of wireless communications suggests that a source signal transmitted towards the destination can be overheard at neighboring nodes. Cooperative communication refers to processing of this overheard information at the surrounding nodes and retransmitting towards the destination to create spatial diversity, thereby to obtain higher throughput and reliability. Most existing work on cooperative communications focuses on investigating various issues at the physical layer because it directly improves link reliability in which the advantages are often illustrated by analyzing signalling strategies based on information theory. However, in practice, cooperative gain may disappear if higher layer protocols are not properly designed. Thus, efficient cooperative communication should not only focus on physical layer operation but also address the MAC layer protocol.

Summary

In recent years, the research focus on wireless cooperative communication is shifting from physical layer to MAC layer. Paper B proposes a contention-based cooperative MAC protocol in wireless networks. While most of the previous work on cooperative MAC design concentrates on one popular cooperation scenario in which a single relay with best link quality among a group of potential relay nodes is selected to do cooperation, the proposed scheme utilizes multiple relay nodes to retransmit the packet over diverse paths so that both spatial diversity and time diversity could be obtained. Since all the relay nodes attempt to access the channel at the same time in the proposed protocol, it is necessary to design an effective scheduling algorithm. Inspired by the persistent RCSMA protocol [89] where all relay nodes will access the channel according to the DCF protocol, we develop a random backoff scheme for each relay to access the channel. While the traditional DCF protocol may introduce long defer time and random backoff time, in the proposed scheme we reduce the backoff stage from one relay node and distribute this time saved to all relay nodes. Furthermore, we assume that the relay channels are independent of each other in the system. Two consecutive packets on the source-destination channel or the relay-destination channel are subject to temporally correlated channel fading and have the same state transition probability.

Main Contribution

The main contribution of this paper is the design of a contention-based cooperative MAC protocol in the presence of multiple relay nodes. The required number of relay nodes is derived according to the relay channel condition. Additionally, we develop a Markov chain to analyze the cooperative MAC protocol. In order to evaluate the performance of the proposed MAC, we compare system throughput and the required number of retransmissions with an ARQ scheme in which the active relay node attempts to transmit the packet as many times as necessary until it is successfully received by the destination node. The simulation results demonstrate that the proposed protocol outperforms the non-cooperative ARQ scheme over error-prone channels.

Related Work

Lots of work have been extensively carried out to explore the new opportunities introduced by cooperative communications, especially at the physical layer which directly addresses the cooperative diversity. For instance, two well-known categories of cooperative schemes have been proposed to exploit diversity gain, namely, Amplify-and-Forward and Decode-and-Forward [65, 91]. Apart from the physical layer, cooperative communications also raise many unique features from the MAC perspective. One of the important issues corresponding to the MAC design is relay selection, which has been proposed to improve reliability in wireless communication systems in many publications [73, 74, 76]. In CD-MAC [70], each node proactively selects a relay for cooperation when it is beneficial in combat with interference from nearby nodes. However, to select a single relay is inherently simple to implement, but it may offer lower gains in terms of system throughput in comparison with the multiple relay node approach which is investigated in Paper B.

5.3 Summary of Paper C

Cooperative MAC Design in Multi-hop Wireless Networks - Part II: When Source and Destination are Two-hops away from Each Other

Problem Statement

Although most existing work on cooperative communications focuses on investigating various issues at the physical layer, the research focus is moving to up layers, especially the MAC layer. However, a dominant majority of existing work on cooperative MAC design concentrates on one-hop source destination cooperation scenario in which a relay node may help retransmitting a packet to the destination node if the direct transmission from source to destination fails. Nevertheless, these schemes are not easily applicable to a network environment where there are lots of multi-hop source-destination pairs.

Summary

When the traditional MAC protocols are applied in multi-hop wireless networks, the performance will degrade due to the intrinsic MAC design. Thus, in Paper C, we propose a Two-hop Cooperative MAC protocol (TC-MAC) specifically designed for two-hop communications. In our scenario, the communication between source and destination has to be forwarded via relay nodes since the source node and the destination node cannot hear each other i. e., no direct communication between source and destination. In this regards, relay selection is of great importance. The main idea behind relay selection is to find optimal additional paths between source and destination for achieving transmission diversity. While in most cooperative MAC protocols, only one relay is preferred to do cooperation, Paper C selects a number of optimal relays for cooperation to provide both time and spatial diversity. More specifically, TC-MAC includes two working modes, i.e., static TC-MAC and adaptive TC-MAC, respectively. While in static TC-MAC the number of required relay nodes is pre-defined, the number of required relay nodes in adaptive TC-MAC, is adaptively obtained according to two-hop combined channel conditions. Among multiple relay nodes, the transmission order is determined by the combined link quality over each relay node. In order to evaluate the performance of the proposed TC-MAC, extensive simulation is performed. The throughput performance of TC-MAC operating on both static and adaptive modes is compared with that of 802.11 in a two-hop network scenario.

Main Contribution

The main contribution of this paper is an elaborate cooperative MAC protocol design for two-hop transmission, which could also be applied in a multi-hop network. Also, in order to maximize the spatial diversity, the concept of MRP inspired by MPR in OLSR is introduced. The simulation results demonstrate that more reliable communications, reduced transmission power and significant throughput improvement can be achieved by TC-MAC, especially when the adaptive alternative of TC-MAC is employed.

Related Work

While the advantages of relay-based cooperative MAC protocols in single-hop scenarios are well documented in a number of studies [69, 102], their impact on multi-hop network performance is not yet fully understood. Recently, how CoopMAC performs in multi-hop ad hoc networks is discussed in the literature [103–106]. In [103], the authors reviewed the issues and challenges on design an efficient cooperative MAC protocol for multi-hop wireless networks. In [104], simulation studies have been done for CoopMAC in multi-hop wireless networks. Although the thorough studies show that the cooperative protocol outperforms IEEE 802.11 in most cases, the authors comment that an interesting field to be investigated is the possible reduction of interference caused by multi-hop transmissions. In [105], directional antenna is used to decrease the interference which is introduced by co-operation. However, additional hardware support is needed which might be not suitable for large-scale applications. Furthermore, although the work above obtains obvious achievements, the effect of hidden station on the performance of CoopMAC in multi-hop wireless ad hoc networks has not been paid adequate attention to.

5.4 Summary of Paper D

A TDMA-Based MAC Protocol Supporting Cooperative Communications in Wireless Mesh Networks

Problem Statement

Wireless mesh networks are deemed as a promising technology in next generation wireless communication systems. However, multi-hop WMNs still have some problems that are not trivial. For instance, when a traditional CSMA-based MAC protocol is used, it is known that the performance will deteriorate in a multi-hop network due to its intrinsic MAC design principle. That is, the contending nodes in the range of its two-hop neighbors can affect channel access opportunity, resulting in serious unfairness and packet collision. On the other hand, although cooperative communication could provide reliable transmission and improve network performance, it also confronts with the same problem that requires to extend the transmission from a single sender-receiver hop to a sender-relay-receiver two-hop scenario. In this case, medium access control plays an important role in determining channel utilization. TDMA protocols could efficiently avoid packet collision and provide fair access for each node in wireless networks with static topology. Nevertheless, how to perform cooperative communication in a TDMA system is still an open question.

Summary

Paper D proposes a TDMA-based medium access control protocol supporting cooperative communications in wireless mesh networks. In a TDMA system, the system time is broken down into time slots of constant duration, and the time slot could be further divided into small parts which are referred to as mini-slots. In the study, the proposed MAC protocol utilizes control mini-slot to dynamically and efficiently allocate channel resource not only for direct transmission but also for cooperative transmission. In addition, access priority is always given to cooperative transmission through an optimal relay node. The optimal relay is determined by fulfilling a timer based-relay selection algorithm which is executed across nodes in a distributed manner. It is worth mentioning that the relay selection time which is normally not negligible could be finished within the inherent time of the system.

Main Contribution

The main contribution of Paper D is the design of a TDMA-based cooperative MAC protocol, which efficiently allocates cooperative communications within the time slot. In addition, two state Markov chains are introduced to analyze wireless channels and the performance of the proposed protocol respectively. To validate the proposed MAC protocol, we have developed a network simulating program by using MATLAB. The effectiveness and the efficiency of this novel MAC scheme have been demonstrated with respect to system throughput, throughput gain in one-hop and two-hop scenarios respectively by considering several factors such as signal threshold, channel error rate, transmission power, hop distances, and network density.

Related Work

There are a limited number of studies on cooperative communications using TDMA, since it is difficult to allocate time slot for cooperative transmissions. In [93], a fixed cooperative relay utilizes the idle time slot available in a TDMA frame and two corresponding MAC protocols are designed to assist packet retransmissions. However, this approach will encounter the difficulty that few or even no slots are available if the network is heavily loaded. C-TDMA [94] attempts to handle this problem in a way that by using its own time slot neighboring nodes help the source node to retransmit the unsuccessful packets. However, due to the sacrifice of its own time slot the neighbor node may confront a situation that no slot to use for its own packet transmission. Therefore, this method will bring unfair transmission into the network which may affect aggregate throughput in a multi-hop wireless network.

5.5 Summary of Paper E

A Cooperative Lifetime Extension MAC Protocol in Duty-Cycle Enabled Wireless Sensor Networks

Problem Statement

A critical constraint on wireless sensor networks is that sensor nodes rely on batteries. A second constraint is that sensors will be deployed unattended and in large numbers, so that it will be difficult to change or recharge batteries in the sensors. Therefore, a primary design principle is not only to reduce the energy consumption of sensor nodes but also to avoid the exhaustion of a single node in order to prolong the lifetime of the entire network. Duty cycle MAC protocols have been proposed as an effective mechanism to reduce energy consumption in wireless sensor networks. Although these protocols could provide efficient energy-conservation solutions, they cannot cope with the energy hole problem in a multi-hop wireless sensor network, where a few nodes near the sink must relay the packets from the rest of the network, and consequently exhaust their batteries earlier.

Summary

Paper E proposes a novel cooperative duty cycle MAC (CDC-MAC) protocol to extend the lifetime of wireless sensor networks. On the one hand, the proposed CDC-MAC adopts the duty cycle MAC concept to prolong each sensor node lifetime. On the other hand, to resolve the energy hole problem, CDC-MAC exploits the benefit of cooperative transmission where range extension could be achieved. Transmission with longer distance could be used to jump over the heavily burdened node and reach the two hop away node directly so that the burdened node could avoid depleting earlier. In brief, CDC-MAC triggers a CT when a node on a primary route to the sink determines through control packet exchange that it has higher residual energy than the next-hop node on the route. The node then recruits cooperators to simultaneously transmit copies of the packet through independently fading channels to extend the range. In order to guarantee that the neighboring nodes are active during the recursion, CDC-MAC works in a synchronous manner. Furthermore, the required number of copies is determined based on the required transmission range to reach the two-hop away node.

Main Contribution

The main contribution of this paper is a duty cycle MAC protocol with cooperative transmission enabled, which could cope with the energy hole problem. In addition, an energy-balance-oriented scheduling algorithm is proposed to schedule corresponding nodes to access the channel. The simulation results demonstrate that the energy consumption levels of sensor nodes are evenly distributed in the network by using CDC-MAC, resulting in more balanced node transmission and energy resource utilization. As a consequence, CDC-MAC could provide significant network lifetime extension in comparison with traditional point-to-point duty cycle MAC protocols.

Related Work

There have been a large number of studies on duty cycle MAC protocols without CT for wireless sensor networks to conserve energy. S-MAC [107] inspires the development of a whole string of energy-efficient MAC protocols. The main contribution of S-MAC is that its fixed duty cycle approach is both simple and effective in reducing idle listening overhead. Additionally, RI-MAC [96] proposes a receiver-initiated asynchronous duty cycle MAC protocol in which each non-sender node broadcasts a short beacon during its active period while a sender just listens to the channel silently and waits for the notification from the receiver. Compared with the prior asynchronous protocols, where preamble transmissions occupy the medium for too long, RI-MAC achieves higher throughput, packet delivery ratio, and energy efficiency. However, few duty cycle MAC protocols address cooperative transmission, which is investigated in Paper E.

Chapter 6

Concluding Remarks

This final chapter first concludes the scientific contributions of the dissertation as a whole and discusses the limitation of this thesis work, and then points out a few directions for future research.

6.1 Summary of the Research and Scientific Contributions

The demand for new generation wireless networks has spurred a vibrant flurry of research activities on multi-hop wireless technology and cooperative communications during the past decade and great advance in this area has been achieved. However, many aspects of multi-hop wireless networks, especially combined with cooperative communications still remain as open questions. For instance, while load balancing in wired networks can distribute traffic across multiple links to avoid congestion, it is unclear if multi-path load balancing can be effectively used in multi-hop wireless networks, since the transmission conditions are very different in such networks. Furthermore, most of the cooperative schemes proposed so far are based on ideal assumptions, such as infeasible synchronization constraints between the relay nodes or the perfect medium access scheduling mechanism among the involved nodes. Therefore, there is a need for research on practical ways of realizing cooperative schemes based on more realistic assumptions.

The objective of this dissertation has been twofold: 1) To investigate load balancing across multiple paths as a possible mechanism to improve routing performance in multi-hop wireless networks; 2) To advance the understanding of cooperative transmission by proposing a number of cooperative MAC protocols. The objective has been achieved through in-depth studies in the field and correspondingly a series of peer-reviewed international publications, two in journals, eight in conference proceedings. In the following, the contributions of this doctoral dissertation are summarized.

- A traffic splitting approach for performance improvement is proposed in wireless mesh networks. By taking advantage of MAC layer information, the status of the network traffic load is predicted. Then based on different traffic types defined at the transport layer, load balancing could be efficiently achieved among all available paths.

- In practical cooperative systems, medium access control is indispensable since more nodes are involved in the cooperation and all of them may attempt to access the channel. We firstly propose a contention-based cooperative MAC in the presence of multiple relay nodes. Considering that the inherent design principle of 802.11 MAC, which is not appropriate for multi-hop communications, we further extend the cooperative MAC protocol for two-hop transmission and even multi-hop networks. In addition, we also develop different categories of MAC protocols for cooperative transmission, i.e., contention-based and contention-free schemes. Furthermore, according to different network requirements, four cooperative MAC protocols are proposed, such as cooperative lifetime maximization MAC for wireless sensor networks.

6.2 Limitations of the Research

In multi-hop wireless networks hop count is critical to the obtained throughput. In other words, the saturated throughput will decrease as the hop count increases and it becomes stable when the hop count reaches around six hops. To be fair, the main idea of the proposed traffic splitting policy is to distribute traffic flows of the same source destination pair along *different* routes according to network congestion status and traffic types, so that better load balancing and channel utilization can be achieved. In other words, those traffic flows go through the same hop count in the original path. However, in practice, this assumption may not be realistic. It is also meaningful to investigate the consequence of splitting traffic flows with different source-destination pairs.

As mentioned in the beginning of the dissertation, without joint consideration and design of physical layer, MAC layer and network layer, the benefit of cooperative communication cannot be exploited to the maximum extent. In this dissertation various cooperative MAC protocols have been proposed according to the cooperation benefits from the physical layer. However, it would be more convincing if we could have evaluated these cooperative MAC protocols in a realistic testbed rather than just simulations. In addition, although the proposed cooperative MAC protocols have been executed in certain network conditions and demonstrated good performance, it is not sufficient since they have not been implemented with any routing protocol in large-scale networks.

6.3 Suggestions for Further Research

The research performed in this dissertation opens up serval directions for future studies. Basically, the issues raised in the previous section can be a topic for future research. For instance, there are still lots of discussions on possible approach to regulate routing cooperation in accordance with increased traffic load. Since both connectivity and congestion may vary in the network, one part of the network may suffer from high node density and congestion, whereas other parts may suffer from node scarcity and weak connectivity. A distributed decision algorithm might enable an overall wise decision.

The merits of the cooperative communications in the physical layer have been explored. However, the impact of the cooperative communications on the design of the higher layers has not been well-understood yet. In particular, the physical information about the wireless medium can be provided to the upper layers in order to provide efficient scheduling, routing, resource allocation, and flow control algorithms. In this dissertation, we have proposed serval cooperative MAC protocols. However, MAC design in cooperative networks is still a challenging and fertile research area. For instance, little attention has been paid attention to cooperative communications in duty cycle MAC protocol.

On the other hand, routing algorithms, which are based on the cooperative communications, are known in the literature as cooperative routing algorithms. Designing cooperative routing algorithms is an interesting and a largely unchartered research area. research area. Most of the existing cooperative routing algorithms are proposed by finding a shortest path route first and then improving the route using cooperative communication. As such, these routing algorithms do not fully exploit the merits of cooperative communications, since the optimal cooperative route might not be same as the shortest path route. A cooperation-based routing algorithm, which makes full use of the benefit of cooperative communications to construct a minimum-metric route, would be a definite direction.

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PART II

A A Novel Traffic Splitting Policy for Performance Improvement in Wireless Mesh Networks

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Title:	A Novel Traffic Splitting Policy for Performance Improvement in Wireless Mesh Networks
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A Novel Traffic Splitting Policy for Performance Improvement in Wireless Mesh Networks

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Abstract — **Wireless mesh networks are expected to play an important role in the next-generation wireless communication systems as it can provide wide coverage and scalable broadband Internet access services. However, as more traffic is injected into the network it may lead to throughput degradation, packet loss and longer transmission delay. In this paper, we argue that network performance can be improved by cross-layer design over multiple layers and load balancing based on service types. Correspondingly, a novel traffic splitting policy which can potentially utilize diverse paths for transmitting traffic flows of different service types from the same router has been proposed and investigated. Such a policy is able to balance traffic load, ideally aggregate capacities across multiple paths and leverage diversity among the paths to achieve low packet loss and more stable throughput.**

I. INTRODUCTION

Wireless Mesh Network (WMN) is a multi-hop wireless network composed of connected mesh router for the purpose of e.g. providing Internet access. WMNs are typically based on IEEE 802.11 due to its distributed nature and ease of implementation. The throughput of such a network is not a fixed quantity, but depends on the efficiency of the Medium Access Control (MAC) protocol used, path loss and signal fading, interference generated by other routers etc. Furthermore, as the numbers of stations and traffic flows increase, the probability of collision may increase dramatically, leading to degraded network performance. On the other hand, WMNs are expected to provide optimized capacity to clients and Quality of Service (QoS) to certain number of flows despite possible congestion status of the network. These requirements lead to the task of performance improvement of WMNs more challenging.

To improve the performance of a WMN, various approaches can be introduced, from MAC and routing enhancement, to load balancing and cross-layer design. In addition to MAC mechanisms and routing protocols themselves, routing metrics are also of significance in order to find most suitable path and forwarding nodes between source nodes and their destinations [1]. A well-selected metric should cover adequate information about the link or path. Each router in the network selects the best path according to the properties contained in routing metric. Due to the co-existence of many interacting parameters such as network load, link transmission rate, intra-flow and inter-flow interference, and link dynamics, the design of efficient routing in WMNs remains a challenging task, from the perspective of cross-layer design. Currently, most cross-layer design approaches consider solely how to use layer 1 or layer 2 information for layer 3 routing optimization [6, 7]. With these approaches, traffic flows with diverse service types may not benefit from the optimal routing path owing to the un-awareness or disharmony between routing metrics and flows' own traffic features.

Load balancing is another efficient approach to resolve the congestion problems in WMNs. It can be achieved through path-based load balancing, gateway-based load balancing or mesh router-based load balancing [12]. In path-based load balancing, the traffic is distributed across multiple paths. In gateway-based load balancing, the load is balanced either among all Internet gateways (IGWs) or a few selected gateways [9]. Load balancing can also be carried out at the mesh routers over the wireless backbone. However, *traditional routing strategy with load balancing intends to direct all traffic flows as a whole to another less loaded path* if the ongoing path could not satisfy the requirements [1, 3, 7], without distinguishing the *types of services*. This strategy may lead to a potential threat that many traffic flows are suddenly redirected to the same path, causing performance degradation on that specific path. Furthermore, as a consequence of this strategy, mesh routers may switch paths frequently back and forth, leading to so-called ping-pong effect with poor service continuity.

In this paper, we propose and investigate the performance of a novel routing strategy which incorporates both cross-layer design and load balancing. By collaboration across layer design over multiple layers, improved network performance is expected. More specifically, the congestion information derived from layer 2 serves as an indicator to initialize load balancing, and the load balancing routing scheme is achieved by separating flows into different available paths, according to their traffic types. This method is referred to as traffic splitting. With our proposed traffic splitting policy, traffic load is distributed over the entire network, resulting in multifold benefits: (a) excessive congestion inside the network is avoided; (b) the network capacity is optimally utilized; (c) packet loss is decreased and total network throughput increased; (d) greater benefit is achieved for the re-directed traffic flows.

The rest of this paper is organized as follows. Sec. 2 reviews some related work. In Sec. 3, we present our traffic splitting policy for efficiently load-balancing over different paths, while the simulation results are observed in Sec. 4. In Sec. 5, we further study factors that affect the results, and based on this study a more detailed algorithm is described in Sec. 6. Finally, the paper is concluded in Sec. 7.

II. RELATED WORK

In this section, we discuss briefly recent work regarding performance analysis of wireless mesh networks, and various proposals for enhancements in WMNs, including load balancing and cross layer design.

In [8], the authors derived a model to eliminate the effect of hidden/exposed nodes in multi-hop wireless networks. They investigated the throughput starvation of flows and showed that the minimum contention window has a more profound effect on mitigating flow starvation than exponential back-off mechanism and RTS/CTS control procedures. [13] observed that in wireless mesh networks the limited number of gateway nodes could be the bottleneck of the entire network. The authors presented a formal study on the delay and throughput of the gateway nodes. They modelled the gateway nodes as independent M/D/1 queue stations, and derived closed-form solutions for the bottleneck delay and throughput with liner and grid topologies.

A major concern about using IEEE 802.11 in WMNs is its inherent unfairness at the MAC layer when used in multi-hop wireless networks. Existing solutions to this problem either do not efficiently resolve this unfairness, or require modifications to the MAC protocol. [11] proposed a co-ordinated congestion control algorithm that achieved max-min fairness over unmodified 802.11 MAC layer. The overhead measurements showed that their algorithm was indeed feasible, and it did yield significantly better performance than existing mechanisms. [2] also proposed algorithms to reach fairness across multi-hop flows for achieving better performance. They measured the available bandwidth as the inverse of per-packet MAC contention and transmission time. Each router then ran a proportional max-min fair bandwidth sharing algorithm to divide this measured bandwidth among the flows passing through it.

There are also many studies for enhancing network performance by distributing the traffic load among the whole network. [7] proposed a routing metric with load balancing for wireless mesh networks. Quantitative and qualitative analysis showed the significance of the proposed scheme, compared with existing similar schemes. In [9], the authors proposed a novel technique that elegantly balanced the load among the different IGWs in a WMN. The point of attachment of an active source is switched among gateways, depending on the average queue length at the IGW. However, without considering cross layer issues, their schemes can not efficiently explore other protocol layer parameters.

In summary, there is a large body of work on improving the multi-hop wireless mesh network performance. However, few of these solutions address the problems from the perspective of cross layer design considering both layer 2 and layer 4, and from load balancing perspective considering service types. Different from the related work, we employ a traffic splitting policy which takes into account parameters in other protocol layers, path capacity, congestion condition, different service types, to balance the load among the whole network to obtain high aggregation throughout.

III. THE PROPOSED TRAFFIC SPLITTING POLICY

In this section, we develop a traffic splitting policy under heavy loaded conditions to provide load balancing in WMNs. The scheme uses congestion status and traffic types as the input for routing decision.

A. Motivation

According to the basic principle in traditional routing protocols, a routing decision is made to find the least-cost path from source to destination, no matter it is based on hop-count or other metrics. Correspondingly, once a proper route from the source node to the destination node is established, all traffic flows will be transmitted through the same route until the routing decision is updated, regardless of which type of traffic is being carried. The main idea behind our traffic splitting policy, however, is to distribute traffic flows of the same source destination pair among *different* routes according to network congestion status and traffic types, so that better load balancing and channel utilization can be achieved.

B. The Proposed Traffic Splitting Policy

In our earlier work [4], a routing scheme which could redirect certain types of traffic to other paths under heavy traffic load has been proposed. In addition, depending on the average MAC layer utilization and network transmission queue length, a combined metric is used to measure the congestion status at each router. In this paper, we further develop the traffic splitting routing policy, which is expected to utilize resources in the whole network more efficiently. The proposed routing policy is shown in Fig. A.1.

As showing in the figure, when more traffic flows are pumping into path 1, instead of redirecting all traffic flows to a better path we will split certain traffic to go through another path, while the rest is still kept on the original path. In other words, this splitting policy has been designed in such a way that different traffic types from the same router may select different paths towards the Internet gateway.

IV. SIMULATION CONFIGURATION AND OBSERVATION OF THE RESULTS

In this section, we carry out extensive simulations to evaluate the performance of our proposed routing scheme using network simulator, ns2. We also provide observation of the simulation results and performance comparison between traditional routing and our proposed routing policy in terms of aggregate throughput and packet loss ratio.

A. Simulation Configuration

In the simulations, we use a small-scale multi-hop wireless mesh network as an example to evaluate the performance of the proposed routing scheme. As shown in Fig. A.2, there are 20 Mesh Routers (MR) consisting of the backbone of the

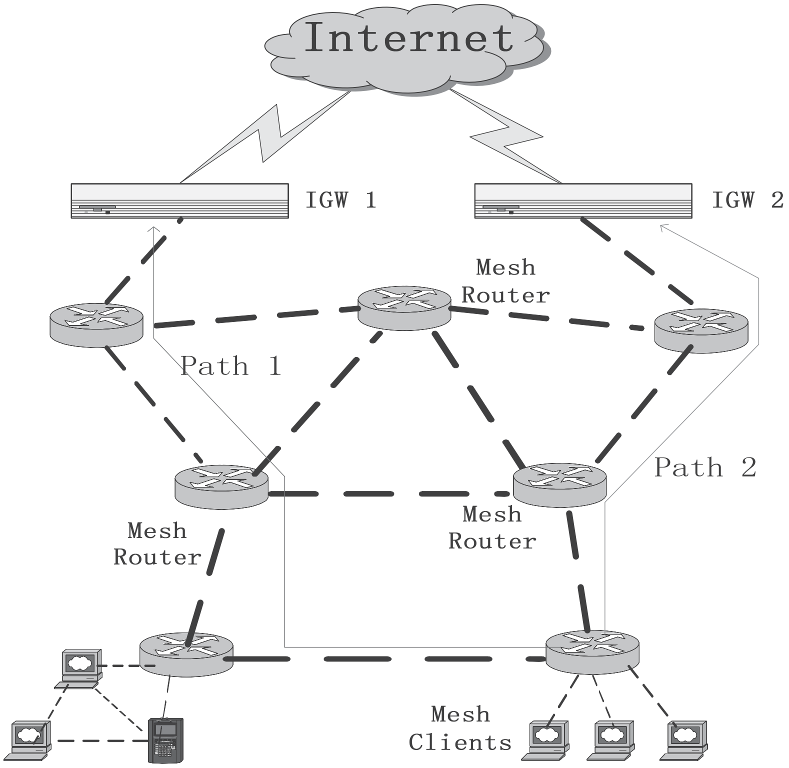

Figure A.1: Illustration of traffic splitting in a wireless mesh network.

wireless mesh network. Stations 1, 2, 3 are connected to MR 11 and station 4 is connected to MR 1. Two gateways, MR 5 and MR 20 are connecting to the Internet. All communications are based on 802.11 DCF. The transmission range is 250 m and the carrier-sensing range is 550 m. In addition, the distance between any two neighboring nodes is set as 200 m. The simulation duration is 300 s. The channel datarate is set to be 11 Mbps.

At MR 11, connecting stations send heterogeneous traffic. Two UDP flows and one TCP flow go through the network from gateway MR 5 or MR 20. At MR 1, a TCP flow is also generated from station 4 to go through the network. In order to saturate the network the traffic generated at source node in a manner that as soon as a packet is transmitted to destination node, another packet is ready for transmission.

In a heavily loaded wireless mesh network, clients may inject more traffic into the network than it can support. In our case, mesh clients S1, S2 and S3 generate more traffic than the saturation throughput.

Ad hoc On-Demand Distance Vector Routing (AODV) [10] is adopted in our simulations. Under the guiding of the legacy AODV, the heterogeneous traffic flows go through the network in the way as shown in columns 3 and 4 of Table 1. That is, all types of traffic go through the same path towards the closest gateway. Different from the legacy routing protocol, our proposed policy allows different types of traffic flows to be transmitted over different paths, even though they are covered from the same mesh router, as shown in columns 5 and 6 of Table 1. For instance, the traffic splitting policy tries to split UDP1 to travel along path 2 towards the Internet

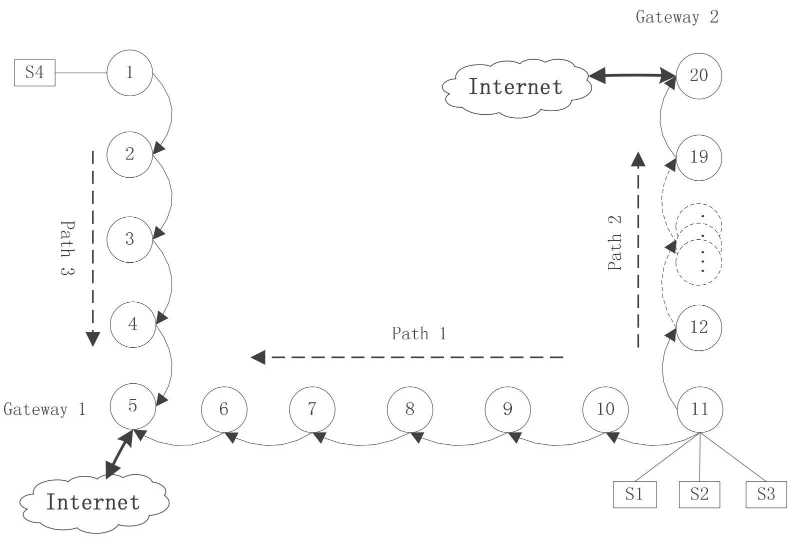

Figure A.2: Simulation topology of a WMN.

Table A.1: Proposed Traffic Splitting Policy vs. Legacy Routing Protocol.

	Src	Legacy routing		Splitting policy	
		Dest	*Next hop*	*Dest*	*Next hop*
TCP1	S1	GW1	MR10	GW1	MR10
TCP2	S4	GW1	MR2	GW1	MR2
UDP1	S1	GW1	MR10	GW2	MR12
UDP2	S1	GW1	MR10	GW1	MR10

through gateway 2 when path 1 is heavily loaded, while other TCP and UDP flows are still using the original shortest path, i.e. path 1. We could also split another type of flows, as described in the next subsection.

B. Observation of Simulation Results

Three cases are studied in our simulations. For our proposed traffic splitting policy, we modify the legacy AODV so that the routing decision is not only based on hop count, but also traffic load and service type. With this modification, we are able to split certain traffic flows into other path while the rest is still kept in the existing path, when the current path suffers from heavy traffic load. In our simulation, the split flow could be TCP traffic or UDP traffic, as specified below.

- Case 1: Traffic flows transmit based on the traditional routing protocol.
- Case 2: The traffic splitting policy is applied, where one UDP traffic flow is split to path 2.
- Case 3: Instead of splitting UDP traffic, one TCP traffic flow is split to go through path 2.

The observed simulation results based on these 3 cases are presented in what follows.

As shown in Fig. A.3, in the heavily loaded network, we can observe that not all of the four traffic flows get opportunities to transmit. Indeed, the TCP flow from MR, TCP 1, 11 did not obtain any throughput. Due to the capacity limit and many competing stations on the same channel, although two UDP traffic flows are able to capture the channel, they have to share the bandwidth and each of them could only get limited throughput owing to time division of occupying the channel and packet collision during the competing. Considering TCP 2, the same reason of single channel limit and common gateway router shared with the rest of traffic flows leads to TCP 2 reasonable throughput.

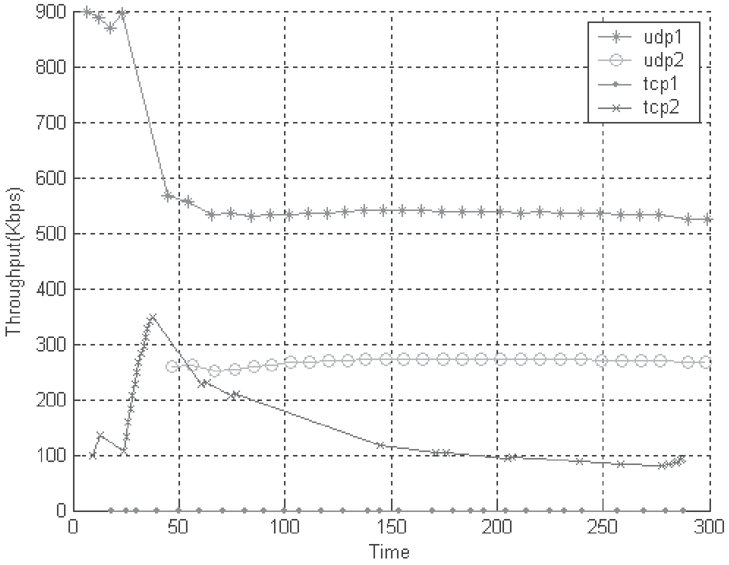

Figure A.3: Throughput of traffic flows in Case 1.

Case 2: By using our proposed traffic splitting approach, as the congestion condition on the current path reaches certain level, one UDP traffic flow is split to another path to attach the Internet through gateway, MR 20. As known from [5], in a chain topology the throughput of the traffic around 6 hops away from the source will converge to approximately 1/7 of the throughput that a single-hop transmission can achieve. For illustration of the throughput result, we take the observation of the achievable throughput of each traffic flow.

As shown in Fig. A.4, the split UDP traffic obtains much higher throughput gain and the total throughput is significantly improved. This is because that the split UDP flow transmitted along the new path has got much higher throughput compared with in Case 1. In Case 1, as the two UDP flows go through the same route, they have to compete to get to access the channel. In addition, owing to link capacity limit in path 1, it will be more difficult for the UDP flows to capture the channel. In Case 2, besides the split UDP flow another UDP flow also gets higher throughput as there is less traffic flow competing for the limited channel capacity. For the traffic flow of TCP 1, it still does not get any throughput due to the failure of competing with UDP traffic flows at the router.

Case 3: Instead of splitting UDP traffic flow we redirect TCP traffic flow to the adverse path in this case. As shown in Fig. A.5, two UDP traffic flows are able to obtain stable throughput. However, the split TCP traffic flow still can not get any throughput. TCP traffic exhibits properties that it will send more and more packets

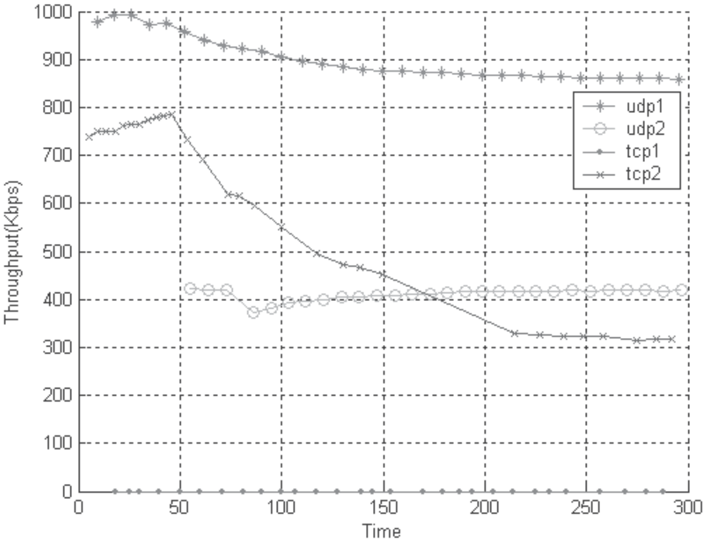

Figure A.4: Throughput of traffic flows in Case 2.

to the network as long as there is enough bandwidth, and vice versa. After unsuccessfully competing with two UDP traffic flows which go through the same router, TCP traffic loses opportunities to access the channel to transmit any packets.

Table A.2: Individual and Aggregate Throughput of Different Flows.

Throughput(Kbps)	UDP1	UDP2	TCP1	TCP2	Aggregate
Case1	525	225	0	93	843
Case2	858	340	0	321	1526
Case3	506	199	0	83	788

Table A.3: Packet Loss Ratio in the Three Cases[1].

Loss ratio (%)	UDP1	UDP2
Case1	87.12	89.82
Case2	78.19	80.67
Case3	87.44	90.63

C. Summary of the Simulation Result

Comparing with the original routing strategy we observe that our proposed policy presents higher aggregate throughput. Table A.2 illustrates that in Case 1 with the traditional routing protocol the aggregate network throughput is only 843 Kbps. However, in Case 2 with our proposed traffic splitting policy the aggregate throughput could reach 1526 Kbps, which is far higher than with the traditional routing.

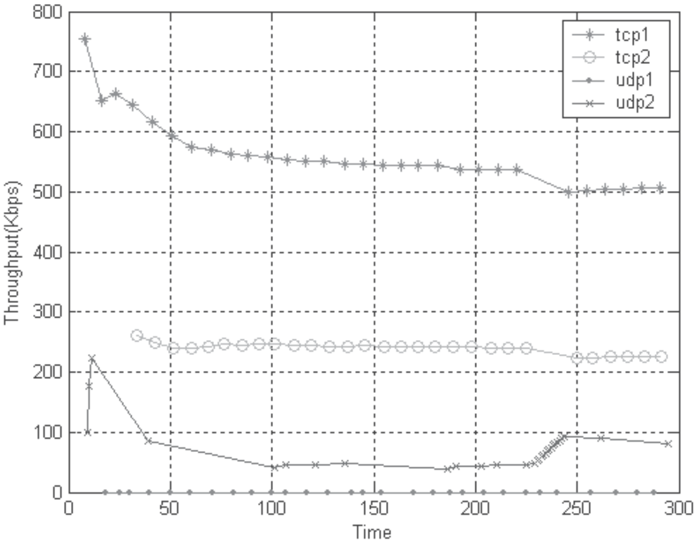

Figure A.5: Throughput of traffic flows in Case 3.

Although in Case 3 we also split certain traffic to another light loaded path, due to the service type of the split traffic the aggregate throughput we can achieve is only 788 Kbps, which is lower than in Case 2 and even lower than in Case 1. As a consequence, we do not recommend traffic splitting for TCP flows. Instead, rate control should be introduced to TCP traffic.

Table 3 shows packet loss ratio result of UDP traffic flows in three cases. Since the TCP traffic flow provided with retransmission mechanism, the dropped packet will be retransmitted if an ACK is not received within timeout. Due to this fact we do not consider the packet loss ratio of TCP traffic flow. It is observed that two UDP traffic flows in Case 2 get moderately less packet loss than in Case 1 and 3. The probability for successful packets transmissions in Case 2 is higher, nearly extra 10 percent of sending packets are able to achieve, indicating the reliability of data transmission is improved significantly.

V. FACTORS AFFECT THE OBSERVED RESULTS

In this section, we study a few factors that affect the network performance introduced by the splitting policy, e.g. the effects by competing stations, hidden terminal and traffic intensity. The performance of three cases will be also compared.

A. Effect by the number of competing stations

Traffic generated by many mesh clients has to compete for channel access at the router. The number of stations will influence the contention probability to obtain the channel. Collisions experienced by each source node suffer from packet loss during transmissions. The collision rate signifies the contention level in the channel, and it follows that higher packet loss implies less coordination among the competing source nodes. With the proposed traffic splitting policy, some traffic flows will be split to another path. Consequently, the number of competing stations along the congested path will relatively decrease, leading to lower collision probability. With less collision, the overall network performance is improved.

B. Effect by hidden-terminals

A fundamental issue in multi-hop wireless networks is that performance degrades sharply as the number of hops traversed increase. In addition to carrier sensing preventing simultaneous transmissions of adjacent hops within the carrier-sensing range of a node, the hidden terminal problem could also decrease system throughout. *However, hidden terminal problem happens only when the hidden terminals have packets to transmit.* With the number of flows increasing on the path, the hidden terminal problem will become even worse. Especially, in a heavily loaded route, more hidden terminals would be active, leading to more serious performance degradation.

By applying our traffic splitting policy, the traffic load on path 1 is reduced. Correspondingly, the effect of the hidden terminal problem on that path will be relieved. In Fig. A.6, we could observe that, with the traditional routing in Case 1 and one of the traffic splitting methods in Case 3, most packet loss happens at MR 11, and the packets are dropped fewer and fewer at the remaining routers to the destination direction. It will also hold this principle in Case 2. We could find that packet loss happens in this case at two directions, and packet loss occurs relatively less than in Cases 1 and 3. What is more, compared with the routing scheme in Cases 1 and 3, the proportion of the packet loss at these nodes decreases dramatically with our proposed policy, which means that both these two paths enjoy higher delivery ratio. The total packet loss ratio among these nodes in Case 2 is far less than in Cases 1 and 3. Consequently our traffic splitting policy greatly eliminates the effect of the hidden terminal in a heavily loaded routing path.

C. Effect of traffic intensity

If more traffic is injected into the network than it can support, it will lead to a congestion problem. For multi-hop wireless mesh networks, if heavy traffic load is transmitting from the first hop, the throughput will decrease as the number of hops increases.

It has been shown in [5] that in a chain topology the traffic flow could not get a sustainable stable throughput until 6 hops away. It is the result of carrier sensing and

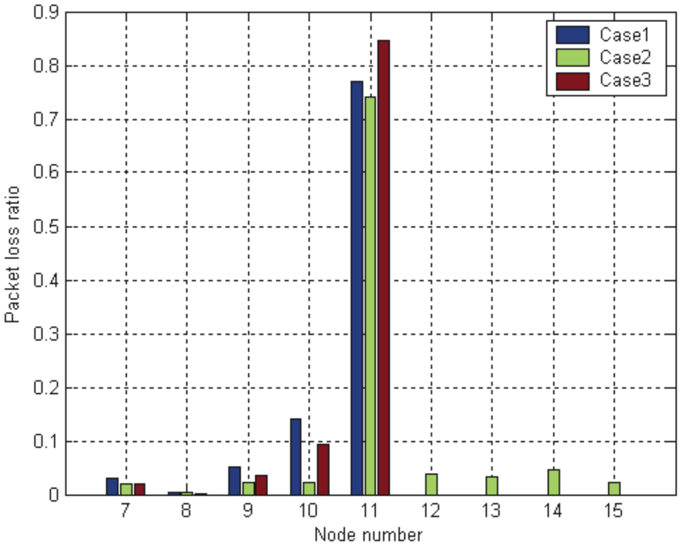

Figure A.6: Distribution of packet loss ratio among the nodes.

hidden-terminal problem which imposes the limitation on channel spatial-reuse and increases the chance of link failure. From the view point of MR 5, when the traffic started at MR 11 reach MR 5 which is 6-hop away from the source node, the total generated throughput more than saturation at first node will decrease approximately to 860 Kbps at the 7th node, which is nearly 19% of one hop saturation throughput. If the traffic generated at MR 11 does not reach the saturation throughput, but more than 860 Kbps, the received traffic at MR 5 will be also 860 Kbps. So we could conclude the network sustainable capacity is 860 Kbps from the view point of MR 5. This is also true for the whole network or even worse if the flow traverse more than 6 hops.

Guided by this principle, in Fig. A.7, it is true at MR 11 that all stations compete for getting access to the same channel. Assuming that in Case 1 under the same condition each traffic generated by the three stations is more than 860 Kbps, then only 860 Kbps could be received. Actually, since TCP 2 generate at station 4 will also go through MR 5 which shares the channel, and TCP 1 comes from the same router with UDP 1 competes to access the channel which leads to packet collision. Indeed, the throughput of path 1 obtaining at MR 5 is 750 Kbps. In contrast in Case 2, as the split traffic transmit from path 2, additional 860 Kbps capacity could be achieved on another path. Although in Case 2 the throughout obtained at MR 5 decreases, from the two curves of Case 2 in Fig. A.7 we could observe that the total throughput on both path 1 and 2 in Case 2 is much higher than the one obtained

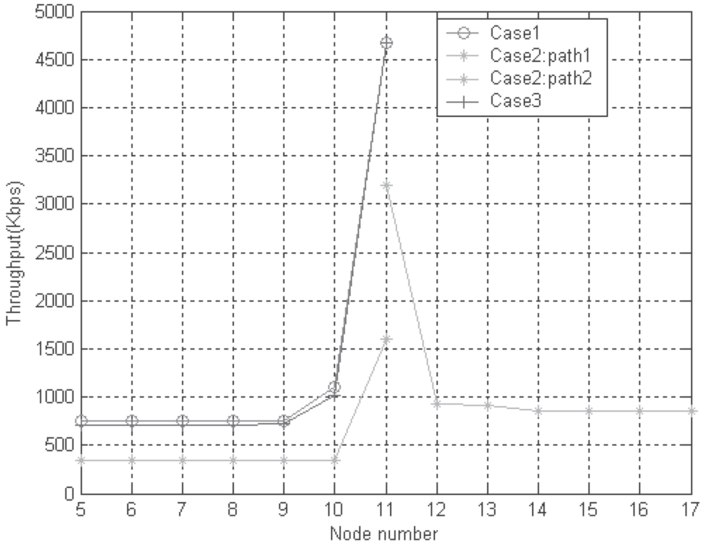

Figure A.7: UDP throughput at different MR in the presence of TCP flows.

in Case 1. The proposed policy admits almost twice as much traffic as the legacy routing protocol could sustain.

Considering these mentioned issues and the earlier conclusion, if more traffic is trying to go through path 1 on which ongoing traffic flows have filled full of the saturation throughput, it should be rejected subject to the network capacity constraint. But if we switch some traffic flows into path 2 which assumes to be relatively lightly loaded, there will be no such capacity limitation, then we could achieve more aggregate throughput by utilizing the resources of path 2.

D. Unfairness among TCP flows

Most of the factors lead to TCP unfairness can be tracked back to unfairness of the IEEE 802.11 MAC protocol. However, the greedy behavior of TCP and its poor interaction with the MAC layer further exacerbate the unfairness situation. Compared with UDP, the adaptivity of the TCP traffic gives it high throughput in a lightly loaded environment and low throughput in a congested environment. In both cases, TCP traffic will have a very low TCP packet loss because of its retransmission scheme.

Generally, TCP tries to send more packets when the network is lightly loaded, and vice versa. There are also periods in which TCP traffic is completely stopped. In our scenario, TCP 2 starts earlier to send packets than TCP 1. We could observe that TCP 2 achieves stable throughput while TCP 1 gets no chance to transmit. As TCP 2 catches the channel and path 3 is lightly loaded, its congestion window size will become larger and larger, sending as more packets as it could. Conversely, TCP 1 fails to transmit due to the unsuccessful competition with UDP flows, and then back-off mechanism aggravates the failure of its transmission. Compared with TCP 2, the contention window of TCP 1 becomes larger and larger, so TCP 1 loses the opportunity while trying to send packets again. This explains the reason for very low throughput of one of the TCP flows in these cases.

VI. DETAILED ALGORITHM DESIGN

Based on the above observations and performance analyses, we design the traffic splitting algorithm with more details as follows.

As mentioned in Sec. 3, when the traffic load condition on the path measured by the combined metric reaches certain pre-defined value, we split certain number of traffic flows from the ongoing path to another one. However, we did not distinguish traffic type when we split the flow to another path, i.e. both UDP and TCP can be split. Through simulations studies, we conclude that, usually, UDP traffic flow will be taken to split to another path if congestion happens. As a consequence, the split traffic flow will get better throughput, and the aggregate network throughput will significantly increase. This performance is improved at the cost of more resource utilization in the newly directed path. Meanwhile, we do not recommend to split TCP traffic, because TCP flow will generate little traffic in the heavy traffic loaded condition. Instead, rate control policy is applied on TCP flows.

The detailed traffic splitting algorithm is shown in the following diagram.

***Algorithm**: Traffic splitting policy*

```
Begin
    At each mesh router
        If the value of the combined metric $<$ Threshold
            Admit this node and follow the original shortest path routing protocol
        End if
        If the value of the combined metric $\geq$ Threshold
            Inform all the mesh routers by
                Sending a Congestion_Notify message using multicast
        End if
    Upon receiving a Congestion_Notify message
        For each path to the gateway
            Select the lightest loaded path from all available paths
```

```
    End for
    Check service type
    If it is UDP
        Then split the traffic flow
    End if
    If it is TCP
        Then apply rate control policy
    End if
End
```

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a novel traffic splitting policy to improve the performance of wireless mesh networks. We study the impact of number of competing stations, hidden terminals, and traffic intensity on the network performance. Through these reasonable and practical analyses, a traffic splitting routing algorithm is proposed. The simulation results demonstrate that our splitting policy can moderately reduce packet loss and significantly increase aggregate network throughput compared with the legacy routing protocol. The great benefit is achieved by the split traffic flow with the aid of better utilizing the resources in the whole network. As our future work, a large-scale network will be tested and rate control on TCP traffic will be studied.

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B A Contention-based Multiple Access Protocol in Cooperative Wireless Networks

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Title: A Contention-based Multiple Access Protocol in Cooperative Wireless Networks

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A Contention-based Multiple Access Protocol in Cooperative Wireless Networks

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Abstract — **Cooperative communication has emerged as a promising technique to enhance system performance in wireless networks. This paper proposes a contention-based cooperative multiple medium access control protocol by means of multiple retransmissions of the same packet from different relay nodes. The proposed scheme exploits cooperative communication capability not only from time diversity derived from multiple temporal transmissions but also spatial diversity derived from distributed multiple relays. A Markov chain is introduced to analyze the throughput performance of the proposed cooperative scheme. The performance evaluation of the protocol is validated and compared with non-cooperative ARQ protocol in error-prone channels.**

General terms: Algorithms, Design, Performance

Keywords—Cooperative communications, Contention-based MAC, Markov Chain.

I. INTRODUCTION

Cooperative communications have become a new paradigm for wireless networks where stations collaborate with each other by creating multiple signal paths from source to destination to relay information. In this way, significant system improvement in terms of network throughput has been demonstrated [4].

Most of the previous work on cooperative transmissions focuses on one popular cooperative diversity scenario which consists of a single pair of source-destination nodes and a group of potential relay nodes. The destination node which receives a data frame from the source node with failure can request one or several of the relay nodes that overhear the original transmission to retransmit the packet. To perform cooperative communication, one solution is to select a single relay which exhibits best link quality or offers highest gains in terms of throughput to retransmit the packet [2, 6]. Another alternative is to use multiple relays so that both spatial and time diversity can be obtained since relay nodes are spatially distributed [5].

In the case of the second solution, there are two types of cooperative schemes to help forwarding the overheard packet. One is the ARQ scheme in which the active relays attempt to transmit their cooperative packet as many times as necessary until the cooperation phase finishes [3]. However, in most cases, the ARQ scheme using the packet coming from the *same relay node* leads to minimal diversity since retransmissions happen over the same channel. Another possible solution operates in such a way that the overheard packets derived from different relay nodes are retransmitted over diverse paths to the destination node, until the destination node is able to decode the original packet by combining different copies of a packet from these relays.

The focus of this study is on the latter scheme where spatial diversity is well exploited. Since all relay nodes will attempt to access the common channel at the same time, it is necessary to design a scheduling algorithm effectively. In the persistent Relay Carrier Sensing Multiple Access (RCSMA) protocol [1], all relay nodes will access the channel according to the DCF protocol, which may introduce long defer time and random back-off time for each relay. Furthermore, it only considers the collision due to contention. Channel condition also has impact on the correctness of packet reception, especially with temporally correlative channels. In order to minimize the impact of back-off time and increase packet delivery probability from all relay nodes which could provide spatial diversity gain, we reduce the back-off stage from one relay node and distribute this time saved to all relay nodes. The throughput performance of this proposed cooperative multiple access protocol is analyzed and evaluated in error-prone channels.

The rest of the paper is organized as follows. The system model is described in Sec. 2, then the proposed cooperative multiple access protocol is presented in details in Sec. 3. The protocol principle and performance analysis are given in Sec. 4, and the performance is evaluated through comparison with the original ARQ schemes in Sec. 5. Finally the paper is concluded in Sec. 6.

II. SYSTEM MODEL

We introduce here the system model to illustrate how our cooperative protocol works. As shown in Fig. B.1, the system model consists of a source node, S, a destination node, D, and n intermediate relay nodes between nodes S and D, i.e., R_1, R_2, $R_3, \cdots$, R_n, which may be used to retransmit data packets to the destination node in the cooperative mode. Therefore, the system model is composed by a total number of $n+2$ nodes, where S and D can hear each other directly and relay nodes can hear both S and D.

Note that the proposed cooperation scheme is executed through a single com-

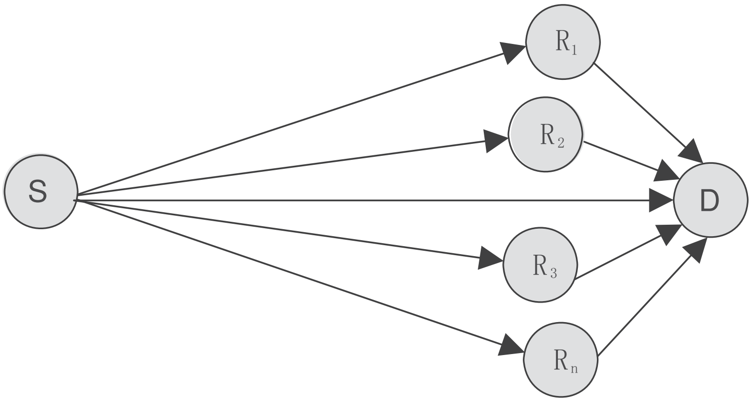

Figure B.1: System model for two-hop cooperative communication.

mon channel. The relay set should be well self-organized and transmit the packet in a time-divided scheduled fashion because only one transmission can occur for each transmission cycle. Otherwise, packet collision will take place. Therefore, efficient MAC mechanism design to schedule that a set of nodes avoid transmitting packet to the same destination at the same time is imperative.

Furthermore, the relay channels are assumed to be independent of each other in the model. Two consecutive packets on the source-destination channel or the realy-destination channel are subject to temporally correlated channel fading and have the same state transition probability, as validated in experiment [7]. In addition, a two-state Markov chain was built to model the channel with time correlation, where ”1” and ”0”, represent that the packet has been received correctly or not, respectively. The transition probabilities have been obtained after using the experiment results to train the model: p_{10}=0.001, p_{11}=0.999, p_{00}=0.97, p_{01}=0.03. These values indicate that the probability of another successful data packet transmission after a successful one on the same channel is as high as 0.999, and the probability of a successful transmission after an unsuccessful one is as low as 0.03, and so on.

There are also other schemes that only the proper relay specified by relay selection criteria is used to do cooperation [2]. Although the optimal relay selection is able to provide the best relay for cooperation, our scheme is to select all relays to forward the packet which loosen the requirement of selecting exactly the most appropriate relay in each moment. The destination node decides how many number of copies from different relay nodes is required to ensure successful decoding. The study on the tradeoff between cost and efficiency of selecting the best relay against the time required to solve the contention among a set of relay nodes is also of interest and deserves for further attention.

III. COOPERATIVE MAC MECHANISM

In brief, the new cooperative MAC protocol works as follows. First, source node S sends a data packet to destination node D. This packet is also received by all nodes in the relay set. If node D is not able to decode the packet correctly, it will ask its neighborhood to retransmit a copy of the same packet in order to reconstruct it. Those nodes that received the original packet will then try to retransmit it to node D one after another. Eventually, node D will properly decode one of the retransmitted frames.

A. Cooperative Mechanism Description

The proposed MAC mechanism is based on the Distributed Coordination Function (DCF) of the IEEE 802.11 standard. The main target of this mechanism is to enable the stations to ask their neighbors to cooperate if the DATA frame was received erroneously. The error-check could be performed by checking a Cyclic Redundancy Code (CRC) attached to the tail of the packet or any other equivalent methods.

The cooperation phrase is initiated by the destination node by broadcasting a Call For Cooperation (CFC) message. Node D sends the CFC packet after the failure of receiving a packet. The CFC packet asks all nodes around node D to retransmit the original overheard data packet until D could successfully decode the packet or the cooperation timeout expires. Upon the reception of the CFC packet, all relay nodes get ready to forward the cooperative packets. Accordingly, the relay nodes will try to access the channel in order to transmit their cooperative information. The proposed MAC mechanism schedules all relay nodes to execute a back-off procedure for channel access. Different from the MAC rules specified in the IEEE 802.11 standard, there are several modifications in our proposed cooperative scheme:

1) Node D will keep receiving copies of the original packet from different relay nodes until the number of copies reaches m, where m indicates the optimal number of required packets to decode successfully. How m is determined is explained in the following subsection. Consequently, there will be an ACK sent out from node D if either one packet is correctly decoded or m cooperative transmissions finish.

2) Assuming that the sub-network formed by the relay nodes works in saturation conditions, all participating relay nodes have a data packet ready to be sent. In order to avoid collision, it is necessary to apply a back-off mechanism at the beginning of each cooperation phase. Thus, every node has its back-off procedure. Different from the standard back-off algorithm of the IEEE DCF, there is only one back-off stage in our scheme. It means the retry limit is set as one. If the retransmission fails, then all nodes start to compete to access the channel again.

3) The destination node determines when the whole cooperation process is completed. The remaining relay nodes that still attempt to transmit the cooperative information will terminate the procedure by overhearing the ACK message.

The operation of the proposed cooperative MAC mechanism is depicted in Fig. B.2. The Network Allocation Vector (NAV) is inherited from the IEEE 802.11 scheme. Additionally, in order to reduce the overhead during a cooperation phase, it is desirable to use the basic access mode. However, in order to protect against packet collision due to hidden terminal, it will be necessary to execute the RTS/CTS handshake for relay retransmissions.

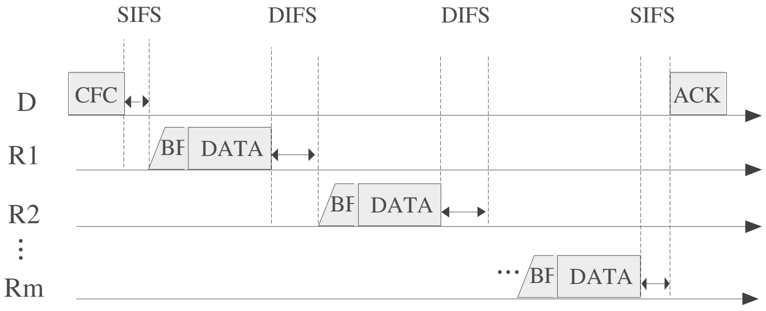

Figure B.2: MAC mechanism.

B. Number of required relay nodes at destination

Consider that the relay channel might also suffer from fading problems, leading to retransmission failure. Although the ARQ scheme could yield improved performance, there is no spatial diversity gain to receive cooperative information from one relay node. In order to attain achievable benefits from multiple relay nodes, several copies of the cooperative information from different cooperative relay nodes via multiple independent channels are preferred. In other words, both spatial diversity and temporal diversity could be achieved when m relays in stead of one are employed.

In [9], a cooperative MAC mechanism by using multiple relay nodes according to relay channel condition is proposed. We borrow the same idea to derive an improved formula of the optimal number of relay nodes.

$$m \approx \min\lceil \frac{1}{(1-P_{id})^2} \rceil, (1 \leq i \leq n), \tag{1}$$

where P_{id} is the packet error rate for the relay channel.

Given the assumption in the system model that all channels are independent of each other, the received link quality is different among relays. If a channel exhibits higher quality, fewer relay nodes are required, and vice versus. Considering the fact that a large number of relay nodes will decrease transmission efficiency due to multiple packet transmission overhead, we define the optimal number of relay nodes according to the node which possesses the best channel link quality, as well as supporting smallest required number of relay nodes.

IV. PERFORMANCE ANALYSIS

A. Analytical Model

There exist in the literature different analytical models to develop accurate expressions of both throughput and average data packet transmission delay for IEEE 802.11 networks. Most of them model the back-off counter of an individual station with a Markov chain, and then derive the overall system performance. Despite the modifications of the medium access rules, it is still feasible to model the back-off counter of each relay node with the Markov chain proposed in [8] for our analysis. In Fig. B.3, the back-off counter value is used to represent the state of a station can take, referred to as state. The counter is initially selected uniformly between $[0,W]$, where is W is the contention window size. The back-off stage always stays the same. If collision happens, the back-off counter of this node will refresh to the maximum value, then every node tries to compete again.

Time slots are considered where a total number of n stations are contending to transmit in each transmission cycle. A slot is defined as the unit of time between consecutive back-off counter decrements. The main assumption of the model is that the probability of having a collision when attempting to transmit in a given time slot, p, is considered to be independent on the state of the station. Therefore, the probability that one station attempts to transmit in a given slot, denoted by τ is derived [8] as

$$\tau = (1+p)\pi_{0,0}, \tag{2}$$

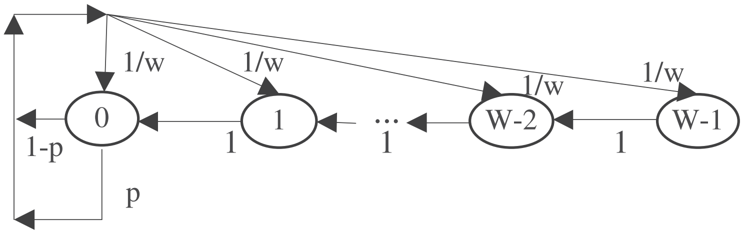

Figure B.3: Markov chain to model the proposed back-off scheme.

where

$$\pi_{0,0} = \frac{2}{W(1+2p)+(1+p)}. \tag{3}$$

Therefore, the collision probability p in a given slot is equal to

$$p = 1-(1-\tau)^{n-1}. \tag{4}$$

Note that we must have $p \in (0,1)$ and $\tau \in (0,1)$. Therefore, the probability that at least one of the n stations attempts to transmit in a given slot, p_{tr}, can be expressed as

$$P_{tr} = 1-(1-\tau)^{n}, \tag{5}$$

and the probability of have a successful slot given that a station transmits, p_s, is given by

$$p_s = \frac{n\tau(1-\tau)^{(n-1)}}{P_{tr}}. \tag{6}$$

It is worth mentioning that these probabilities depend on the number of relays and the back-off contention window size. They will be used to analyze the system performance in the following subsection.

B. Performance of the traditional ARQ Scheme

In the IEEE 802.11 DCF scheme the system time is broken into virtual time slots (transmission cycle) and each slot is the time interval between the packet sent out from the relay nodes and the packet received at the destination node. Note that a node cannot avoid transmission error by receiving the packet over error-prone channels. In the ARQ scheme, if the transmission fails from source to destination, the source node will attempt to retransmit the same packet over the source-destination channel till the packet is received successfully by the destination or the retransmission limit expires. Therefore, the saturated system throughput in the temporally correlative channel is analyzed in Sec. 3 could be written as

$$\eta = \frac{E[P](1-p_e)+\sum_{i=1}^{\lambda} E[P]p_e p_{01} p_{oo}^{\lambda-1}}{(\lambda+1)E[T_d]}, \tag{7}$$

where p_e is the packet error rate of the source-destination channel, λ is the required number of retransmission to satisfy the successful decoding at the destination. $E[P]$ is the average payload data transmitted in a virtual time slot, $(\lambda+1)E[T_d]$ is the total time required to complete such packet transmissions. It depends on whether the basic access mechanism or the collision avoidance RTS/CTS handshake is executed by the nodes. Note that the RTS, CTS and ACK frames are always transmitted in the lowest rate while the DATA frames are transmitted at various rates based on the link quality.

$$T_d^{basic} = T_{DATA} + T_{ACK} + DIFS + SIFS + T_{BF}, \tag{8}$$

$$T_d^{rts} = T_{DATA} + T_{ACK} + T_{RTS} + T_{CTS} + DIFS + 3 \cdot SIFS + T_{BF}, \tag{9}$$

T_{DATA} and T_{ACK} are the transmission times of the DATA packet and ACK packet, respectively. T_{RTS} and T_{CTS} are the transmission times of RTS and CTS packets. $SIFS$ and $DIFS$ are, respectively, the duration of DIFS and SIFS silence periods. T_{BF} is the average back-off time duration.

C. Performance of the Proposed Cooperative Scheme

When the original transmission fails, a number of m copies of the data packets are required in the destination to ensure successful decoding[1]. Therefore, similar to the IEEE 802.11 DCF scheme, the saturated throughput η presented here can be written as

$$\eta = \frac{E[P](1-p_e) + p_e E[P](1-\prod_{i=1}^{m} p_i)}{E[T_d] + E[T_r]}, \tag{10}$$

where p_i is the packet error rate over these error-prone i.i.d relay channels. Since many active relay nodes attempt to access the channel simultaneously, the calculation of the average time to finish the required packet transmission is different from the previous case. From the perspective of medium access, the average time spent on the channel to observe the transmission of a packet payload consists of two events. The first event counts for the average time spent in order to transmit a packet successfully. The second event represents the average time wasted on the channel due to contention.

$$E[T_r] = E[T_{succ}] + E[T_{cont}]. \tag{11}$$

$E[T_{succ}]$ is the average expected cooperation packet transmission delay, which could be only achievable in the case of a perfect scheduling among all the relay nodes, i.e., avoiding contention delay. However, the contention process among re-

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[1] Note that the packet may be correctly decoded before m copies are received. Thence, the analytical throughput here is a lower bound value in practice.

lay nodes is unavoidable. We use $E[T_{cont}]$ to denote the expected delay caused by contention when relay nodes attempt to access the channel. Therefore, the term $E[T_{succ}]$ can be computed as

$$E[T_{succ}] = T_{CFC} + 2 \cdot SIFS + T_{ACK} + T_N, \tag{12}$$

where T_{CFC} is the transmission time of the CFC packet, T_N is the time needed to retransmit the required number of packets from different relay nodes. It depends on whether the collision avoidance is used or not, and thus

$$T_N^{basic} = m \cdot T_{DATA} + (m-1) \cdot DIFS, \tag{13}$$

$$T_N^{rts} = m \cdot T_{DATA} + m \cdot T_{RTS} + m \cdot T_{CTS} + (m-1) \cdot DIFS + 2m \cdot SIFS. \tag{14}$$

On the other hand, since the contention time of a packet is independent of the contention time of the other packets, the value of $E[T_{cont}]$ can be calculated as

$$E[T_{cont}] = m \cdot E[T_c], \tag{15}$$

where $E[T_c]$ is the average contention time required to transmit a single packet among all relay nodes. Furthermore,

$$E[T_c] = (E[X]-1)E[T_{slot\_cont}]. \tag{16}$$

$(E[X]-1)$ is the average number of non-successful slots before having a successful transmission. $E[X]$ is derived in [1] as

$$E[X] = \sum_{j=1}^{\infty} (j+1)(1-P_s)^j P_s = \frac{1}{P_s}, \tag{17}$$

where P_s is the probability of having a successful slot, which can be expressed as $P_s = P_{tr} p_s = n\tau(1-\tau)^{n-1}$. $E[T_{slot\_cont}]$ is the average duration of a slot, given that the slot is not successful. It is decomposed into two events. The first event is the average idle time, can be denoted as $P_i = 1 - P_{tr}$, and the duration is equal to the basic slot time σ. The second represents the average time wasted on the channel because of collisions, $P_c = P_{tr}(1-p_s)$. Therefore, the average duration of any slot that the transmission is not successful can be expressed as

$$E[T_{slot\_cont}] = \frac{P_i}{1-P_s}\sigma + \frac{P_c}{1-P_s}T_{col}, \tag{18}$$

where the duration of the collision T_{col} also depends on whether the collision avoidance scheme is used or not.

$$T_{col}^{basic} = T_{DATA} + DIFS, \tag{19}$$

$$T_{col}^{rts} = DIFS + SIFS + T_{RTS} + T_{CTS\_Timeout}. \tag{20}$$

Consequently, the throughput can be obtained by substituting Eqs. (17) and (18) into Eq. (16), substituting Eqs. (15) and (12) into Eq. (11).

V. PERFORMANCE EVALUATION

We compare the performance of our cooperative multiple access protocol with the traditional ARQ scheme without cooperation, for both the basic scheme and the RTS/CTS scheme. The parameter values based on the IEEE 802.11g are summarized in TABLE E.1. In every transmission, different number of potential relay nodes are generated to connect the source node and the destination node.

Table B.1: Configuration parameters.

Parameter	Value	Parameter	Value
Slot	9 μs	ACK, CFC, CTS	14 bytes
SIFS	10 μs	RTS	20 $bytes$
DIFS	28 μs	MAC_header	34 $bytes$
DATA	500 $bytes$	PHY_header	32 $bytes$

It is well known that the CW size affects the performance of any IEEE 802.11-based MAC protocol if there is an unbalance between the CW size and the number of stations accessing to the channel. As discussed in Subsec. 4.1, the curves of packet collision probability versus the number of relay nodes are plotted in Fig. B.4. It is observed that small CW will lead to high collision probability. On the other hand, large CW will result in long back-off time. Therefore, the CW size should be adaptively selected based on the number of relay nodes in the cooperation phase.

In Fig. B.5, we compare the saturated throughput achieved by the proposed cooperative protocol and the traditional ARQ protocol under varying channel conditions. Both the basic and RTS/CTS cooperative schemes could attain higher throughput than the traditional ARQ scheme in error-prone channels. As channel becomes worse, all the achieved system throughput decreases. However, the obtained throughput of cooperative scheme decreases slower than the traditional scheme because the spatial diversity obtained from different relay nodes is more

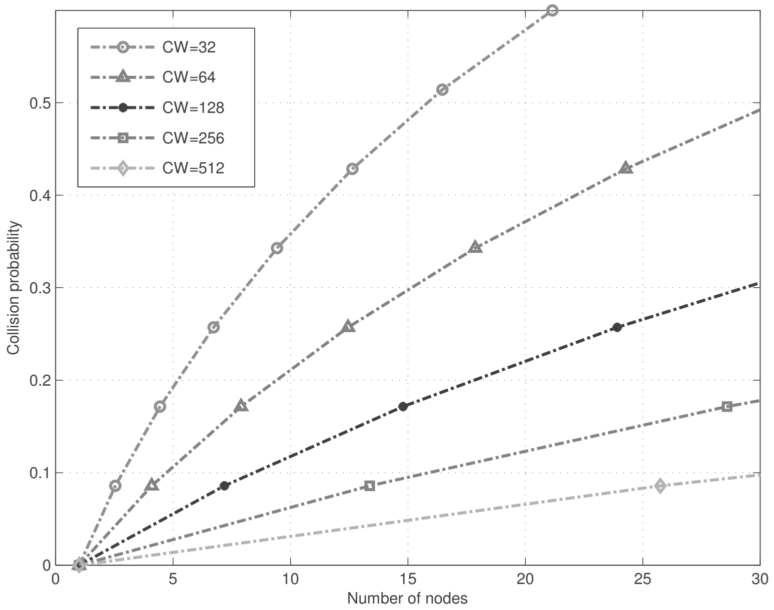

Figure B.4: Collision probability vs. number of relays.

evident than the time diversity exploited by direct retransmission in the temporally correlated channels. Especially, when collision avoidance is applied, the relay nodes could collaborate well with each other. Thus, the throughput of cooperative RTS/CTS scheme decreases more slowly compared with the basic scheme, and gets even higher than the basic scheme when the channel quality deteriorates.

In the non-cooperative ARQ schemes, it has been assumed that the number of required retransmissions from the source is equal to m. Since the source-destination channel might be worse than the relay channels, the number of required retransmission may be higher than m. In Fig. B.6, we compare throughput of both protocols as the number of retransmissions varies. It is observed that as the channel becomes worse and the required number of retransmission increases, the cooperative scheme obtains higher throughput than that of the traditional scheme. The reason is due to that the contention time costs among the relay nodes is less than the time used to retransmit a packet over the temporally correlated channel. Moreover, when the collision avoidance scheme is used, it outperforms the basic scheme in all investigated cases. The cooperative scheme with RTS/CTS attains even higher throughput than the traditional scheme with RTS/CTS when more than 3 retransmissions are required. This benefit comes not only due to its high efficient multiple medium access algorithm but also from the spatial diversity exploited from different relays.

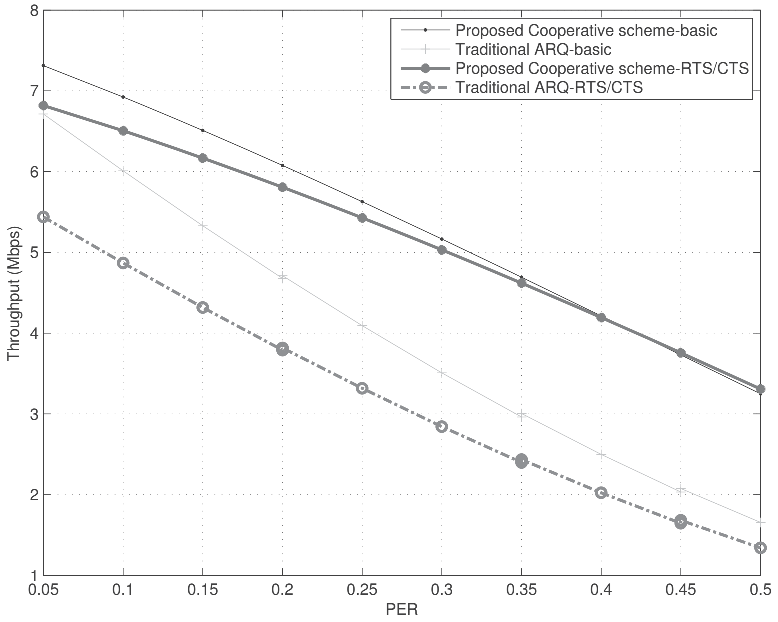

Figure B.5: Throughput in different PER range.

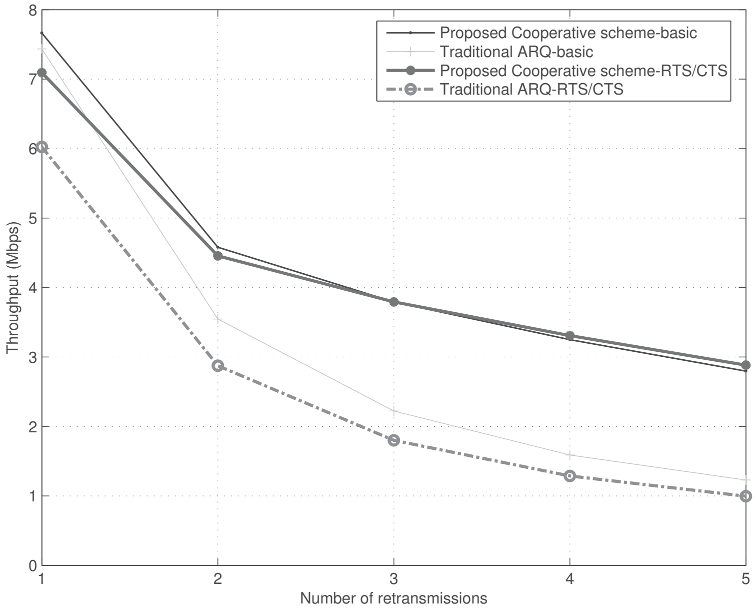

Figure B.6: Throughput vs. number of required retransmissions.

V. CONCLUSION

In this paper, we have proposed a novel contention-based multiple access protocol for cooperative wireless networks. Any destination node which receives a data packet with errors will request the potential relay nodes to retransmit the same packet. This introduces a challenge from MAC design point of view since all relay nodes will attempt to access the channel at the same time. Our proposed protocol adequately takes into account the trade off between the defer time due to contention and collision probability. A Markov chain model characterizing the network operation is built for our performance analysis. Numerical results shows that by using the proposed scheme overall system throughput can be significantly improved under different channel conditions.

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C Cooperative MAC Design in Multi-hop Wireless Networks - Part II: When Source and Destination are Two-hops away from Each Other

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Title:	Cooperative MAC Design in Multi-hop Wireless Networks - Part II: When Source and Destination are Two-hops away from Each Other
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Cooperative MAC Design in Multi-hop Wireless Networks - Part II: When Source and Destination are Two-hops away from Each Other

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Abstract — **Ubiquitous and pervasive computing and networking are envisaged as part of the future 5G wireless communication landscape where devices which are multi-hops away from each other are connected in a cooperative way. In this paper, we investigate a challenging case in cooperative communications where source and destination are two-hops away from each other. From the perspective of MAC design, we propose a novel MAC protocol which enables two-hop cooperative communications by involving one or more one-hop neighbors of both source and destination as the relays for cooperative communication. To do so, a concept referred to as Multiple Relay Points (MRPs) has been introduced and the MRPs are selected by jointly considering the link quality of both hops. In addition to employing a static scheme which always uses a fixed number of relays for cooperative communication, we have also proposed an adaptive scheme which can optimally adjust the number of relays flexibly according to channel conditions. Through performance evaluation and comparison with the original IEEE 802.11 based scheme, we demonstrate that more reliable communications, reduced transmission power and significant throughput improvement can be achieved by using our two-hop cooperative MAC protocol, especially when operated in the adaptive mode.**

Keywords—5G, Two-hop cooperative communication, MAC protocol, Relay selection.

I. INTRODUCTION

While 4G mobile communication is on its way towards standardization and commercialization, researchers are already envisaging the scenarios for further 5G wireless networks. Imagine the existence of ubiquitous wireless devices in such networks with or without infrastructure support and these diverse devices are spread in a distributed network with multi-hop communication capability. Cooperation communications with the help of different devices appear as a promising approach for improving system performance in such wireless communication paradigm.

Cooperation communications were originally proposed as a means to overcome unreliable transmissions by exploiting time, frequency and/or space diversity achieved from multi-paths. In a wireless network with multi-hops, a feasible solution to support cooperative diversity is to forward packets from source to destination by appropriately selected intermediate nodes. However, existing work [4, 5, 7, 9] in this direction has traditionally focused solely on one-hop source destination cooperation under which a relay node R may help retransmitting a packet to the destination node D if the direct transmission from source node S to D fails [6]. A fundamental assumption for one-hop cooperation communication is that the transmitter can reach the receiver directly. Under this assumption, most existing MAC protocols are limited to a single one-hop source-destination scenarios, although few of them, e.g., [4] may also operate in a two-hop source-relay-destination manner if the one-hop direct transmission fails [1]. These schemes are not facilely further applied to a network topology where many multi-hop source-destination pairs exist.

In this paper, as an effort towards cooperative communication in multi-hop wireless networks, we propose a Two-hop Cooperative MAC protocol (TC-MAC) specifically designed for two-hop communications. A salient distinction between this work and existing cooperative MAC protocols is that in our scenario the source node and the destination node cannot hear each other, i.e., no direct communication between source and destination is possible. In other words, the communication between source and destination has to be forwarded via relay nodes which are one-hop neighbors of both source and destination. In TC-MAC, two working modes exist, i.e., *static TC-MAC* or *adaptive TC-MAC*. With static TC-MAC, the number of MRPs is always fixed [3]. Alternatively when the adaptive TC-MAC scheme is employed, the number of required relay nodes can be dynamically adjusted according to combined two-hop channel conditions. For example, as channel condition deteriorates, more relay nodes are selected in order to provide higher spatial diversity gain.

The rest of the paper is organized as follows. The system model is described in Sec. 2. After the relay selection algorithm is introduced in Sec. 3, the proposed cooperative MAC protocol is presented in details in Sec. 4. Performance analysis is then given in Sec. 5, and the performance is evaluated in Sec. 6. Finally the paper is concluded in Sec. 7.

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[1] Indeed, the first transmission attempt in CoopMAC [4] is still one-hop direct communication.

II. SYSTEM MODEL AND ASSUMPTIONS

As illustrated in Fig. C.1, the system model consists of a source node, S, a destination node, D, and a number of intermediate relay nodes, i.e., R_1, R_2, $\cdots$, R_n, which may act as relays to retransmit data packets to destination node in a cooperative manner. The network in the model works in a two-hop fashion, which means that relay nodes $R_i(1 \leq i \leq n)$ are the one-hop neighbors of both source node S and destination node D; D is a two hop neighbor of S; and S cannot directly transmit data packets to D. In addition, relay nodes R_i do not have to hear each other, which means that they may be hidden terminals to each other.

In the system model, all channels are assumed to be independent of each other and the Packet Error Ratio (PER) for each channel is assumed to be uncorrelated for two consecutive transmissions. According to our protocol, each cycle of cooperative transmission will start from S to R_i, then followed by the transmission(s) of the same packet from R_i to D. Based on channel conditions the source node will make a decision on how many and which relays will forward the packets. Then all the selected relays will forward the packet to D, in a coordinated manner.

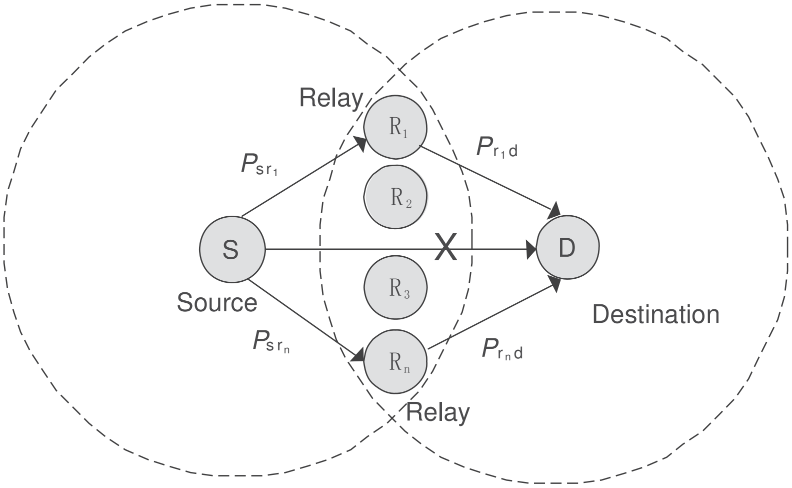

Figure C.1: System model for two-hop cooperative communication.

III. RELAY SELECTION ALGORITHM

A. The Concept of Multiple Relay Point and Neighbor Information Acquisition

In contrast to the concept of Multipoint Relay (MPR) defined in Optimized Link

State Routing (OLSR) [2] in which a one-hop neighbor is selected to forward packets to as many as possible two-hop neighbors, we introduce a concept of MRP in which one or more one-hop neighbors are selected as relays to forward packet to the same two-hop destination. While the purpose of using MPR is to reduce overhead for routing message broadcast in ad hoc networks, the idea of introducing MRP is to achieve spatial diversity in multi-hop cooperative wireless networks through multipath transmissions by MRP nodes. As illustrated in Fig. C.1, there exist n nodes which are one-hop neighbors of both S and D. However, only a selected number of potential relay nodes which satisfy the relay selection criterion belong to the forwarding set, MRP.

Under the proposed relay selection scheme, each source node must detect channel conditions to the destination node via all possible one-hop neighbor nodes. The same as in [2], the one-hop and two-hop neighbor information as well as their link quality status are obtained and maintained by exchanging HELLO messages between neighbors, in a proactive manner. Based on such a neighbor and link information database, the source node selects one or more neighbors which have the highest end-to-end link quality as the MRPs for its cooperative transmission.

The number of MRPs used for each cycle of cooperative transmission is determined based on channel condition obtained through HELLO messages. Upon receiving a HELLO message from a one-hop neighbor, a node is able to extract its two-hop neighbor information. Through the same procedure, the source node in our system model will know all one-hop and two-hop neighbors as well as the associated link quality. Consequently, a database including both neighbor and link information is established by the source node.

B. Multiple Relay Points Selection

Based on the established neighbor and link info database, a set of one-hop neighbors will be selected by the source node as the MRPs for cooperation communication. Since both of these two hops are important for end-to-end performance, we take link quality of both hops into consideration for MRP selection. An MRP set is composed of a selected m $(1 \leq m \leq n)$ number of nodes from n relay candidates which exhibit best combined link quality connecting source and destination. As an indicator, $h_i = \frac{2}{\frac{1}{|a_{si}|^2}+\frac{1}{|a_{id}|^2}} = \frac{2|a_{si}|^2|a_{id}|^2}{|a_{si}|^2+|a_{id}|^2}$, indicates the combined link quality for an end-to-end link, where a_{si} indicates the link quality between source node S and relay node R_i, a_{id} indicates the link quality between relay node R_i and destination node D.

Based on the obtained h_i values for all possible paths between S and D, an m number of nodes with highest values will be selected as MRPs by the source node.

When $m = 2$, for instance, the top two paths with highest h_i scores will be selected.

C. Optimal Number of MRPs and Transmission Order

With each specific channel condition, there will be an optimal number of MRPs which maximizes system performance. In order to obtain the optimal number of MRPs, we use the same method as in [8]. It is suggested that the best size of the cooperation group is around $\frac{1}{(1-P_{si})(1-P_{id})}$, where P_{si} is denoted as the probability of unsuccessful packet transmission in the primary channel between source and MRP candidates, approximatively taken as PER and P_{id} is the PER for the relay channel between the MRP candidates and destination. Since $\frac{1}{(1-P_{si})(1-P_{id})}$ is not a whole number in general, the optimal cooperation group size will be rounded to an integer.

Given the assumption in the system model that all channels are independent of each other, the received link quality is different from path to path among various relays. If channels exhibit high quality, then fewer MRPs are required, and vice versa. Considering the fact that each MRP experiences different channel condition resulting in a different number of required MRPs and that a large number of relay nodes may decrease transmission efficiency, we define the optimal number of MRPs according the relay candidate which provides the *best combined channel link quality* as

$$Optimal\ number\ of\ MRPs = min\lceil \frac{1}{(1-P_{si})(1-P_{id})} \rceil,\ \ i = (1,...,n). \tag{1}$$

Note that the proposed cooperative protocol is operated on a single common channel, which implies that only one transmission can occur at any time. In order to avoid packet collision, the relay set should transmit the packet subsequently in a coordinated fashion and avoid simultaneous transmission of multiple MRPs.

In [1], a relay transmits the packet one by one according to its own measured timer. The relay nodes of which timer expires first will transmit the cooperative information. Due to the uncertain values of the SNR for channel conditions which decide the value of the timer, it might be inefficient to use relay's own timer to transmit. For instance, two consecutive relays with approximate SNR values will send the packets in a short time interval, which may lead to packet collision. Hence, it is necessary to select a centric node, if possible, to fairly schedule the packet forwarding. With our system model, the source node is able to play such a central role. The strategy is that all relays will start to send the cooperative packet with a *constant time interval*, which means that there are m priority numbers for each relay node to access the channel. These priority numbers are derived from the combined link quality h_i. For example, the first and second relays in our scheme are selected as

$$\begin{aligned} h_1 = arg_{\forall j} max\{h_i\}, j \in \{decoded\ MRP\ index\}, \\ h_2 = arg_{\forall j} max\{h_i\}, j \in \{decoded\ MRP\ index\}, j \notin \{h_1\}. \end{aligned} \tag{2}$$

Unless two or more nodes have the same priority numbers, possible collision caused by cooperation could be avoided. In our scheme, we apply a method that compares the absolute value of h_i. Thus, the occurrence that two MRPs hold the same transmission order is avoided.

Based on the above description, a priority-based back-off counter for all MRP nodes is made according to their channel conditions. With this order pre-assigned, the relay node with the best channel quality will have the smallest priority back-off counter and forward the data packet first. While the first relay node is transmitting packet to the destination node, the other MRP nodes will detect that the channel is occupied and freeze their counter until the transmission finishes. The rest of the transmission procedures may be deduced by analogy. Consequently, by means of the priority order of MRP transmissions, it is feasible to avoid packet collision during the relay transmissions.

IV. ADAPTIVE COOPERATIVE MAC PROTOCOL DESIGN

In this section, we present the proposed TC-MAC protocol with two alternative cooperative modes, i.e., the static cooperative scheme and the adaptive cooperative scheme, respectively.

A. The Static TC-MAC Cooperative Scheme

In the static cooperative scheme, if there is only one MRP required, the TC-MAC protocol works similar to the original 802.11 Distributed Coordination Function (DCF) scheme when used in the two-hop case, except that the random back-off mechanism in the second hop is replaced by a scheduled transmission from the relay node in our case. When more than one MRPs are required, the static TC-MAC scheme will work according to the message exchange sequences as shown in Fig. C.2. Two MRPs are assumed here for the purpose of illustration. In brief, the static TC-MAC works as follows: 1) Obtain individual channel quality for both one-hop and two-hop links, and establish a neighbor and link database; 2) Calculate the overall two-hop combined link quality; 3) The source node decides which two MRPs will be used for packet forwarding; 4) The frame transmission sequence follows what is shown in Fig. C.2.

When node S has packets to transmit, it starts to sense the channel. If the channel has been idle for a DCF Interframe Space (DIFS) period a data packet will be sent after S has completed the required back-off procedure. Due to the broadcast nature of the wireless communication, all nodes around S will overhear the packets, no matter it is MRP or not. However, only the MRPs will forward the successfully received data packets. Meanwhile, the Network Allocation Vector (NAV) field associated with the transmitted and forwarded DATA frames will prevent possible transmissions of other nodes rather than S, R_i and D. As mentioned earlier and illustrated in Fig. C.2, the transmission of the second relay happens immediately after the first relay finishes its forwarding with a Short Interframe Space (SIFS) interval, no matter the first relay transmission is successful or not.

In the presence of multiple relays, MRPs which are out of each other's sensing range may forward the packet during the same time interval, resulting in packet collision at the destination node. To avoid collision, each MRP will follow its transmission order instructed by the source node from its original DATA frame transmission. Consequently, each of them will start its own timer T_k proportional to the priority order to forward the DATA frame, as

$$T_k = (k-1) * (SIFS + T_{DATA}), \tag{3}$$

where T_{DATA} represents the time used for transmitting the DATA packet and k is the priority order. Since the relay nodes may not be able to hear each other, each MRP needs to calculate its starting instant for DATA frame forwarding. This is done by reading the Physical Layer Convergence Protocol (PLCP) header of the ongoing transmitting packet sent out by S, which contains the duration of the being transmitted DATA frame.

When R_i is forwarding the DATA frame, S will receive the implicit ACK by overhearing the data frame forwarded to D and decoding the header of the packet to compare with the original data packet. If it was the same packet that S just sent out, then S will know the MRP has already successfully received the packet.

After all relays have forwarded the data frame to D, the reception phase at the destination node will be performed and upon successful reception of the DATA packet, an ACK will be multicast to all MRPs. When the ACK frame sent by D is received, the MRPs will forward it to S. That is, a two-stage ACK process is needed in TC-MAC, due to the fact that S and D cannot hear each other directly. Again, the MRP with best channel condition will forward the ACK to S. Upon receiving one ACK, S could initiate another round of packet transmission. However, in case that S for any reason does not receive the ACK by R_1, the MRP with the second best path quality will start to forward the ACK according its priority order, after

$(T_{ACK} + SIFS)$. Although the redundant ACK may bring overhead for the protocol, it could increase transmission reliability. Correspondingly, as long as S receives one ACK, one cooperative transmission cycle is completed. However, if S does not get any ACK during time interval $m(T_{ACK} + SIFS)$, a new cooperative transmission cycle will be initiated.

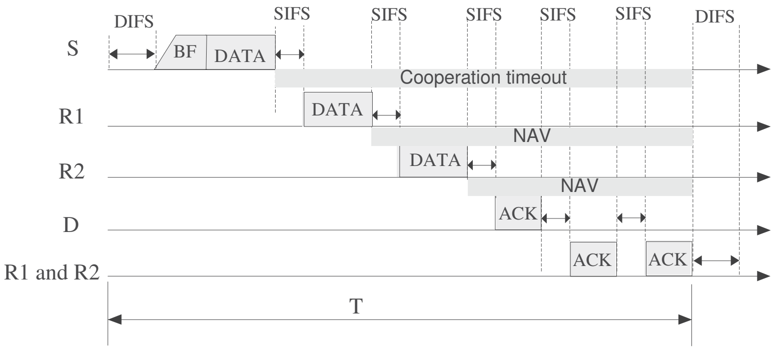

Figure C.2: Cooperative scheme by two MRPs.

B. The Adaptive TC-MAC Cooperative Scheme

As discussed in last Sec. III, the optimal number of MRP nodes may vary as channel condition changes. In this subsection, we propose an enhancement to the static scheme by adaptively employing an optimal number of MRPs for each cooperative transmission cycle. The adaptive TC-MAC scheme could operate flexibly on both one MRP and a large number of MRPs. It works in a similar way as the static scheme does, but the difference is that the number of MRPs employed for each round cooperative transmission may vary in each transmission cycle. The adaptive TC-MAC scheme works as follows: 1) The same as the first two steps as in the static scheme; 2) The source node decides how many MRPs will be employed for the next transmission cycle as well as their transmission order; 3) The same as Step 4) in the static scheme; 4) For each new cooperative transmission cycle, go to Step 1), no matter the previous cycle is successful or not.

V. PERFORMANCE ANALYSIS

Similar to the IEEE 802.11 DCF scheme, the system time can be broken down into virtual time slots where each slot is the time interval between the instant when a packet is sent out from the source node and the instant when the packet is received at the destination node. The normalized system throughput, denoted as $\eta = E[B]/E[T]$, is defined as the successfully transmitted payload bits per virtual time unit, where *E[B]* is the expected number of payload information bits successfully transmitted in a virtual time slot, and *E[T]* is the expected length of a virtual time slot. E[B] can be further expressed as: $E[B] = P_{succ} * L$, where P_{succ} is the probability of successful transmission and a function of per-hop packet failure probabilities, P_{si}, P_{id}, as explained below.

A. Analysis of the Original 802.11 DCF Scheme Operating in a Two-hop Manner

When the original 802.11 DCF-based scheme is used in a two-hop transmission manner[2], the total successful transmission time is the sum of time duration at Hop 1 and Hop 2, which are calculated below respectively. It is worth mentioning that there is a back-off period in each hop in this case. This means that the relay node has to compete with other nodes for channel access before it forwards the DATA frame to D.

$$E[T_{succ}^{orig}] = T_{hop1} + T_{hop2} = 2 * (T_{DATA} + T_{ACK} + DIFS + SIFS) + E[T_{BF_1}] + E[T_{BF_2}]. \tag{4}$$

In the above equation, T_{BF_1}, T_{BF_2} is the back-off time duration of the transmission starting at the source and relay node respectively. Furthermore, we assume that the packet is successfully transmitted by a relay node R, then the probability of successful transmission in this path will be

$$P_{succ}^{orig} = (1 - P_{sr}) * (1 - P_{rd}). \tag{5}$$

Finally, the throughput for the original scheme can be obtained by inserting P_{succ}^{orig} and $E[T_{succ}^{orig}]$ into the expression η.

B. Analysis of the TC-MAC Cooperative Protocol

Without loss of generality, we study the performance of the cooperative scheme by using two MRPs, and then extend the results to more MRPs. Eventually, we derive the performance of the proposed adaptive cooperative scheme based on the static scheme. According to the MAC design in Fig. 3, the total successful transmission time of an ideal cycle is calculated in a two-hop manner, defined as T_{succ}^{coop}. Note that different from the original 802.11 scheme, there is only one back-off period during the whole transmission cycle in TC-MAC, which is executed at the source node. Therefore, T_{succ}^{coop} can be obtained as

$$E[T_{succ}^{coop}]_{2-MRP} = 3 * T_{DATA} + 2 * T_{ACK} + 4 * SIFS + DIFS + E[T_{BF}], \tag{6}$$

$$P_{succ}^{coop} = 1 - [1 - (1 - P_{sr_1}) * (1 - P_{r_1 d})] * [1 - (1 - P_{sr_2}) * (1 - P_{r_2 d})], \tag{7}$$

where P_{succ}^{coop} denote the probability of successful transmission in TC-MAC with two MRPs.

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[2] We assume that S, R$_i$ and D are roughly synchronized in the calculation.

Similarly, we could extend the analytical result to cases with more than two MRPs in cooperation. The successful transmission time of one ideal cycle by one source node and m MRPs will be

$$E[T_{succ}^{coop}] = (m+1) * T_{DATA} + 2 * T_{ACK} + (m+2) * SIFS + DIFS + E[T_{BF}], \quad (8)$$

$$P_{succ}^{coop} = 1 - \prod_{i=1}^{m}[1-(1-P_{si})*(1-P_{id})], \quad (9)$$

where m is the number of MRPs, P_{succ}^{coop} is the probability of successful transmission through these paths. Finally, the throughput performance of the adaptive TC-MAC protocol is the upper envelop among the curves which represent the performance with 1, 2, ..., m numbers of MRPs for each range of SNR.

VI. PERFORMANCE EVALUATION

We compare the throughput performance of TC-MAC operating on both the static and the adaptive modes with that of 802.11 in a two-hop network scenario. The network topology is the same as shown in Fig. C.1. The payload length is set to be 500 bytes. The length of the MPDU header and ACK packet are 24 and 14 bytes, respectively. All the other default parameters in this study are configured according to the IEEE 802.11a standard. For every cycle of cooperative transmission, different number of potential relay nodes are generated to connect the source node and the destination node. The channels between any two transmission pairs are modeled as Rayleigh fading channel, independent of each other and with identical PER.

To compare the throughput performance between TC-MAC and two-hop DCF, we have defined a specific performance indicator as the ratio between η^{coop} and η^{orig}, as $\alpha = \frac{\eta^{coop}}{\eta^{orig}} = \frac{P_{succ}^{coop} * E[T_{succ}^{orig}]}{P_{succ}^{orig} * E[T_{succ}^{coop}]}$. When α is plotted in our performance evaluation curves, it indicates that the proposed scheme outperforms if $\alpha > 1$. On the contrary, if α is smaller than 1, the original scheme performs better.

A. System Throughput based on Different Channel Conditions

Fig. C.3 depicts the obtained system throughput based on different channel conditions, both with the adaptive TC-MAC scheme. One of the curves is obtained based on the best relay channel, while the other one is achieved by a poorer quality relay channel with a PER twice as high as the other case. As explained earlier, different channel conditions will lead to different optimal number of MRPs when adaptive TC-MAC is used. From this figure, it is easy to find that the system throughput based on a better relay channel will always achieve higher throughput. Furthermore, the difference between these two curves becomes smaller as channel

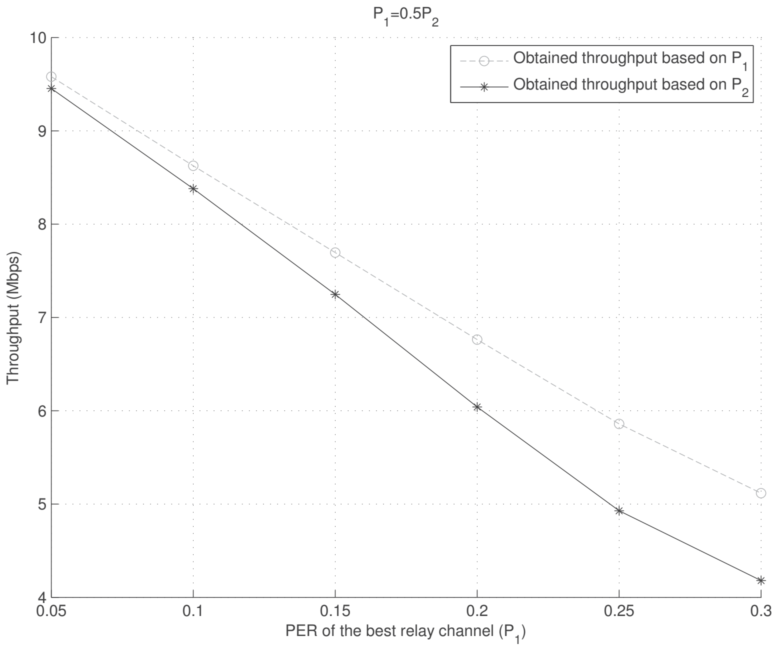

Figure C.3: System throughput based on different channel conditions.

conditions improve. On the other hand, as channel condition deteriorates, there is an apparent decrease in the slope for both curves. The one based on the poorer relay channel decreases more quickly.

B. Throughput Comparison: Static vs. DCF

The throughput of the static TC-MAC protocol with $m = 1,2,3$ respectively is illustrated in Fig. C.4, in comparison with the original DCF scheme when used in two-hops. One can easily observe that in most cases the proposed static TC-MAC scheme outperforms the original DCF mechanism with respect to the obtained two-hop system throughput. This is because that the benefits introduced by our scheme are achieved not only from the reduction of transmission time but also from the spatial diversity exploited.

More specifically, if the channel condition is very good, e.g., $PER < 0.16$, the scheme with 1-MRP will perform best. This is because that one transmission per hop would be sufficient for the successful reception of the DATA packet over two hops. When PER is somewhere between 0.16 and 0.80, employing multiple MRPs would lead to better performance. For instance, when the packet error rate is 0.3, the throughput is enhanced by 72% with the two MRPs cooperative scheme. On the other hand, if the channel is almost error-free, i.e., PER is close to zero, the scheme with three MRPs has lead to lower throughput than the legacy DCF scheme. This is

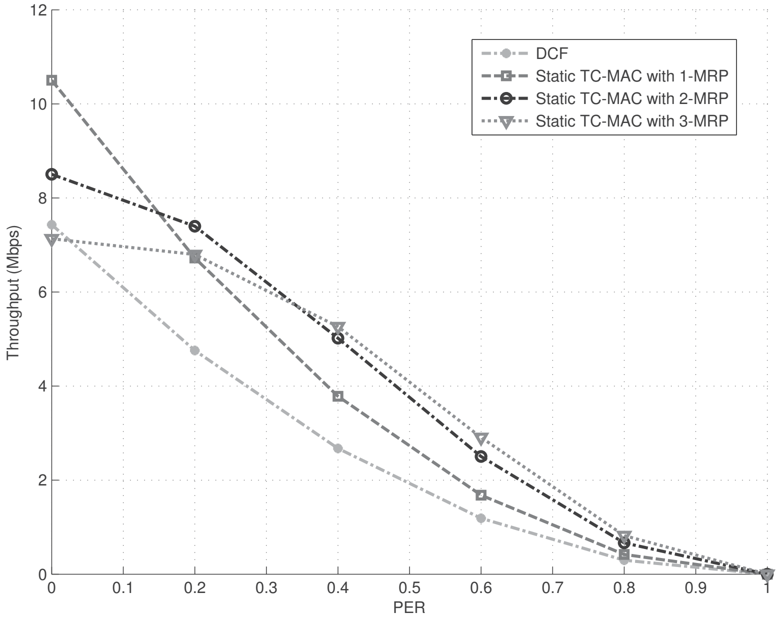

Figure C.4: Throughput performance comparison: original versus static cooperative.

because too much protocol overhead is introduced with three MRPs since the destination node will wait until all three forwarded copies have arrived before decoding.

Furthermore, if the optimal number of MRPs is equal to or larger than 3, the throughput gain will increase but not significant anymore. It is observed that when the PER is higher than 0.35, the achieved throughput by the 3-MRP scheme is higher than that of the 2-MRP scheme, but not much higher. This observation indicates that the benefits may be comprised by the protocol overhead if too many relays are employed. In the worst case where the PER is extremely high, almost zero throughput is achieved for all schemes because all paths failed to deliver data.

C. Throughput Comparison: adaptive TC-MAC versus static TC-MAC

Fig. C.5 shows the throughput gain of the proposed TC-MAC schemes versus DCF, by using α as the performance indicator. Again, the curves demonstrate that the static scheme with one-MRP and two-MRP always have higher two-hop throughput, which means that the cooperative MAC mechanism works more efficiently than the original DCF scheme. When dividing the SNR values into several regions, we observe that the three-MRP scheme exhibits higher throughput gain than the other schemes in the low SNR regions. In the high SNR regions, the one-MRP scheme will perform best, as shown on the right-side hand of Fig. C.5. Based on these observations, the adaptive TC-MAC scheme always takes the advantage of

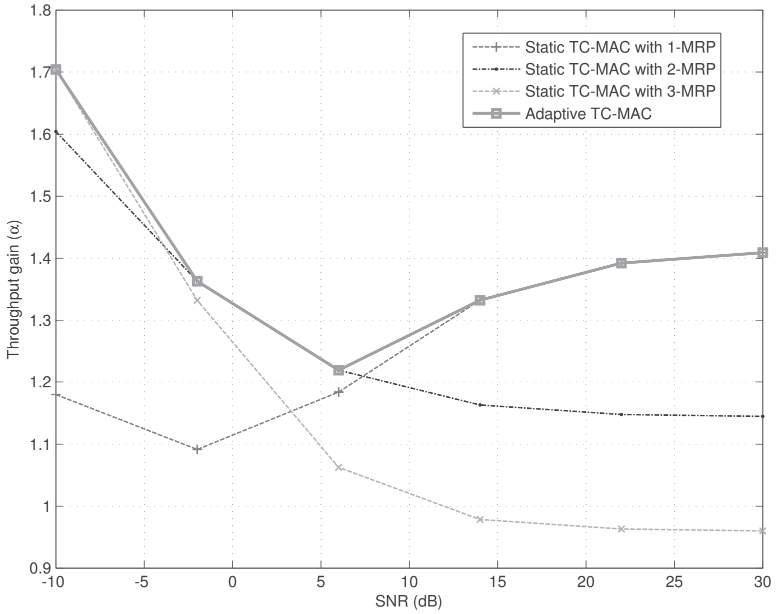

Figure C.5: Throughput gain of TC-MAC compared with IEEE 802.11 two-hop transmission.

the best envelop of the curves derived from the static numbers of MRPs. In other words, we could always get maximum throughput gain under any channel conditions when the adaptive TC-MAC scheme is employed.

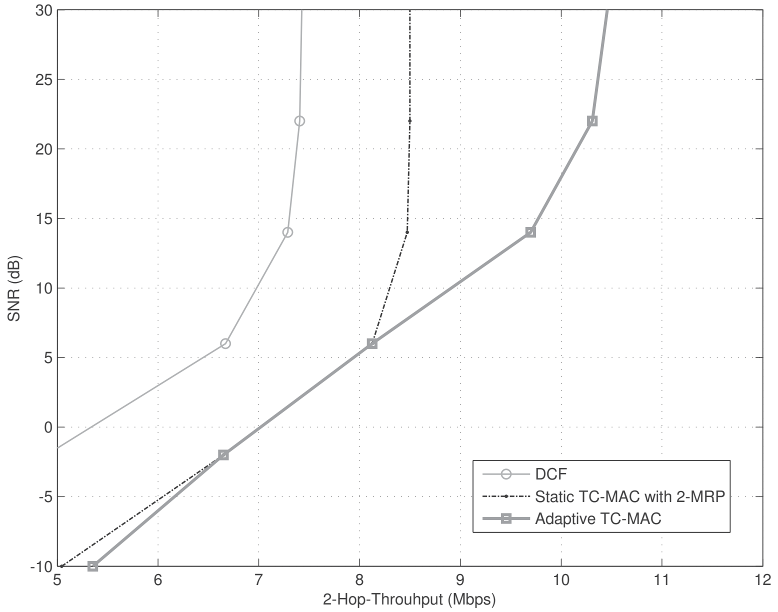

Figure C.6: Average SNR versus throughput.

D. Achieved Throughput versus Transmission Power

Fig. C.6 illustrates the required average SNR versus throughput for the adaptive TC-MAC scheme, the static scheme with two-MRPs and the DCF scheme in a two-hop transmission scenario. As shown in the figure, in order to obtain the throughput level at 6 Mbps, the scheme with two-MRPs requires only an average SNR of around -5 dB, while the DCF scheme requires an SNR of 3 dB. With the adaptive TC-MAC, moreover, only -6 dB SNR would be sufficient to provide the same level of system throughput.

Furthermore, lower SNR requirement can be interpreted as lower transmission power requirement. Given that the network topology and channel conditions are the same for all schemes in our performance evaluation, this result demonstrates that the required transmit power can be greatly reduced to reach the same throughput performance when the proposed TC-MAC protocol is used.

VII. CONCLUSIONS AND FUTURE WORK

Multi-hop networks exhibit a constituent paradigm in the picture of future 5G wireless communication landscape. In such an application scenario, how to perform cooperative communication among wireless devices which are multi-hops away from each other becomes a challenging task. The main contribution of this work is that a two-hop cooperative MAC protocol which deals with the case of no direct communication between the source and destination nodes has been proposed. The study investigates the trade-off between the number of relay nodes and channel conditions in order to take full advantage of spatial diversity for system performance improvement. The numerical results demonstrate that compared with the non-cooperative and the static cooperative schemes, significant throughput improvement can be achieved by employing a dynamic number of relay nodes for cooperative communications. How to extend TC-MAC into larger-scale multi-hop wireless networks as well as studying its performance remain as our future work.

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D A TDMA-Based MAC Protocol Supporting Cooperative Communications in Wireless Mesh Networks

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Title:	A TDMA-Based MAC Protocol Supporting Cooperative Communications in Wireless Mesh Networks
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A TDMA-Based MAC Protocol Supporting Cooperative Communications in Wireless Mesh Networks

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Abstract — **This paper proposes a TDMA-based medium access control protocol which enables cooperative communications in multi-hop wireless mesh networks. According to the proposed scheme, each router at the two-hop neighbourhood of each other is allocated to a specific time slot for accommodating either direct or cooperative transmissions in a coordinated manner, controlled by mini-slots which are part of the time slot. Benefiting from the elaborate mini-slot design, channel resources are fairly and efficiently allocated to each router so that no handshake is needed prior to each packet transmission. By providing access priority to cooperative transmission through an optimal relay which is determined by combined instantaneous relay channel conditions, higher system throughput can be achieved. To analyze the performance of the proposed cooperative protocol a Markov chain is introduced to model the behavior of the protocol. Simulation results demonstrate that the proposed MAC scheme can improve not only the one-hop transmission throughput but also the end-to-end throughput significantly. Moreover, the throughput performance of the proposed scheme is robust as packet size varies.**

Keywords—Cooperative communication, MAC mechanism, TDMA, relay selection, throughput performance.

I. INTRODUCTION

Wireless Mesh Networks (WMNs), characterized of high spectrum utilization, dynamic self-organization and low deployment cost, are regarded as a key technology in next-generation wireless communication systems [2, 4, 9]. A typical topology of WMNs consists of wireline gateways, wireless routers, and mobile stations, organized in three-tier architecture. A mesh router in such a network will forward packets on behalf of other routers that are not within the direct transmission range of their destinations, in a multi-hop manner.

However, multi-hop wireless mesh networks still have some problems that are not trivial. The first one is the end-to-end throughput degradation due to multi-hop transmissions. In multi-hop WMNs, neighbors have to compete for channel access, leading to less opportunity for each node to transmit packets. In addition, the hidden terminal and exposed terminal problems that occur between the links within multiple flows from source node to destination node could also severely degrade system throughput in a heavily loaded network. Moreover, it is possible that any of the links in the multi-hop transmissions suffer from transmission errors, due to either packet collisions or channel fading.

There are lots of proposals in the literature to deal with the above problems. From protocol layer point of view, many solutions are investigated at the PHY layer. For instance, Adaptive Modulation Coding (AMC) can be applied to improve channel efficiency [5], and BPSK could provide robust transmissions at a cost of low data rate. Another alternative is Automatic Repeat reQuest (ARQ) scheme which could boost packet delivery ratio at the link layer. However, traditional ARQ schemes which are developed for wireless channels with random errors will be less efficient in the wireless networks where packet errors emerge as bursts other than randomly [6]. For instance, in a high temporal correlative channel, the retransmission from source node may suffer from the same error as in the original transmission [20].

Furthermore, all these solutions are passively dealing with the problem occurring in one specific link without considering other benefit one may obtain from other links. By means of providing diversity gain through diverse relay links, cooperative communication has appeared as a promising way to improve network performance [12, 17, 21–23]. However, cooperative communications will confront with the same difficulty that it also requires to extend transmission from a single sender-receiver hop to a sender-relay-receiver two-hop scenario. In this case, medium access technique plays an important role in determining channel utilization, especially end-to-end throughput. Due to the extra transmission phase of packet forwarding, the overhead and transmission delay may compromise the cooperation gain if the Medium Access Control (MAC) mechanism is not properly designed.

Contention-based schemes such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) are dominantly explored in the literature for distributed WMNs. However, when a traditional CSMA-based MAC protocol is used, it is known that the performance will deteriorate in a multi-hop network due to its intrinsic MAC design principle. This is because that the contending nodes in the range of its two-hop neighbors can affect channel access opportunity, resulting in serious unfairness and packet collision. Although RTS/CTS can alleviate the hidden terminal problem, it comes at the cost of high overhead. In order to avoid the aforementioned packet collision and hidden terminal problem, Time-Division Multiple Access (TDMA) can be adopted since it schedules transmission time instances of neighboring nodes to occur at different time slots. In this way, packet transmission of each link can be controlled without collision. As a result, the end-to-end throughput will be significantly improved. However, applying TDMA into multi-hop wireless mesh networks could lead to problems such as synchronization, and efficient time slot allocation. While synchronization can be provided by a Global Positioning System (GPS) based solution, how to efficiently schedule each transmission at different time slots, especially for cooperative transmissions, still remains as a challenging task.

In this paper, we propose a novel TDMA-based cooperative protocol in multi-hop wireless mesh networks. By receiving the same copies of the original packet derived from cooperative link with diversity gain, system throughput could be improved with the help of cooperative communication. In [19], cooperation is executed in idle slot which means that cooperation is available, only if there exists free slot. Inspired by the idea of [24], the proposed MAC protocol makes use of control mini-slot to dynamically and efficiently allocate channel resource not only for direct transmission but also for cooperative transmission. In addition, access priority is always given to cooperative transmission through an optimal relay node. The optimal relay is determined by fulfilling a timer based-relay selection algorithm which is executed across nodes in a distributed manner. Moreover, a two state Markov chain is introduced to analyze the performance of the proposed protocol. Simulation results demonstrate that the proposed MAC scheme could improve system throughput significantly.

The rest of the paper is organized as follows. Related work is summarized in Sec. 2, and then the system model is described in Sec. 3. After the proposed cooperative MAC protocol is introduced in details in Sec. 4, Sec. 5 presents the relay selection scheme. The performance analysis is carried out in Sec. 6. Following that, the system performance is evaluated and compared with other three popular schemes in Sec. 7. Finally the paper is concluded in Sec. 8.

II. RELATED WORK

A. TDMA MAC Protocols in (Multi-hop) Wireless Networks

In [24], the authors proposed a TDMA based contention-free MAC protocol for a single-channel wireless mesh backbone to provide Quality of Service (QoS) support for multimedia applications. Without the need for RTS/CTS handshake prior to each packet transmission, the overhead is greatly reduced. In [7], the authors proposed a dynamic subcarrier utilization method using Orthogonal Frequency-Division Multiplexing (OFDM) to balance data rate among each link in TDMA multi-hop wireless networks. In order to transmit data flow without self-interference among flows, two time frames and two frequency bands are introduced. Additionally, seamlessly adapting the MAC protocol between TDMA and CSMA according to the level of the contention in the network was investigated in Z-MAC [25]. A probabilistic TDMA scheme is employed in Z-MAC in which time is slotted to adjust access probability for users under high contention while it behaves like CSMA under low traffic load. However, Z-MAC is designed for one-hop wireless network and does not deal with many difficulties that multi-hop networks face. Funneling-MAC [1] is also a hybrid approach where nodes close to the sink employ TDMA since this area is exposed to high traffic load while nodes far away from the sink use CSMA in order to decrease latency. As a consequence, nodes at the edge of both areas must apply both MAC schemes, which is a complicated task. Furthermore, without taking cooperative communications into consideration, these MAC protocols might not efficiently combat channel fading which may happen in each link in a multi-hop wireless network.

B. Cooperative MAC Protocols

COMAC [8] is a cooperative medium access control protocol designed based on the widely adopted IEEE 802.11 MAC protocol. By considering different physical layer data rates, variable transmission range and network size, it enables cooperation in a realistic scenario and leverages cooperative communications by making use of the overhead packet from neighboring nodes of a source node. CoopMAC [14] is also an 802.11-based cooperative MAC protocol that increases the aggregate throughput in a way that high data rate nodes assist low data rate nodes to forward their data packet. In CD-MAC [15], each node preselects a relay for cooperation and enables it to transmit simultaneously by using distributed space time coding to obtain optimal network performance. However, the intrinsic nature of CSMA that requires nodes to access the medium only if it is sensed as idle can severely limit the effectiveness of not only the direct transmission but also the cooperative transmission [13].

Since CSMA-based multiple access control schemes are not efficiently suitable to obtain potential gains from cooperation, one trend for cooperative MAC design is shifting to schedule-based MAC schemes. In [19], the authors proposed a multiple access approach based on an idea in which the relay node utilizes the empty time slot available in a TMDA frame to launch cooperation. However, this approach will encounter the difficulty that few or even no slots are available if the network is heavily loaded. In [16], the authors proposed a protocol for scheduled TDMA scenarios based on network coded retransmission. However, they did not mention how to allocate cooperative transmission in the scheduled time slot. C-TDMA [26] attempts to handle this problem in a way that by using its own time slot neighbour nodes help the source node to retransmit the unsuccessful packets. However, due to the sacrifice of its own time slot the neighbor node may confront a situation that no slot to use for its own packet transmission. Therefore, this method will bring unfair transmission into the network which may affect aggregate throughput from a multi-hop point of view.

To summarize, TDMA-based MAC protocols are becoming popular in wireless mesh networks thanks to their high efficiency and feasibility in static topologies. However, how to introduce cooperative communications into a TDMA MAC protocol in an efficient way still remains as an open question.

III. SYSTEM MODEL

In this study, we consider a wireless mesh network where the mesh backbone is shown in Fig. D.1 as an example. In this example, a traffic flow generated at source router S is transmitted to destination router D via intermediate router I in a two-hop transmission manner. A number of mesh routers with dashed line are deployed around routers S, I and D. We assume each router is able to overhear its one-hop neighbors' transmission. The overheard packet is temporally stored at the router till the next overhead transmission comes. In case any of transmission fails in one of the two links, i.e., the S-I link or the I-D link, other routers within the coverage area could help forward the packet. Each router may join several cooperation groups depending on its position, capability and willingness to cooperate [5].

IV. THE PROPOSED COOPERATIVE MAC SCHEME

A. Time Slot Structure

The system time is broken down into time slots of constant duration, which are allocated to each router in a distributed manner. In order to avoid packet collision and increase resource utilization, the one-hop and two-hop neighbors of a router are allocated to different time slots. It implies that the same slot could be allocated to routers which do not interfere with each other. As shown in Fig. 2, in the proposed cooperative MAC scheme one time slot consists of three portions, as control part, data part and acknowledgement part respectively. The control part

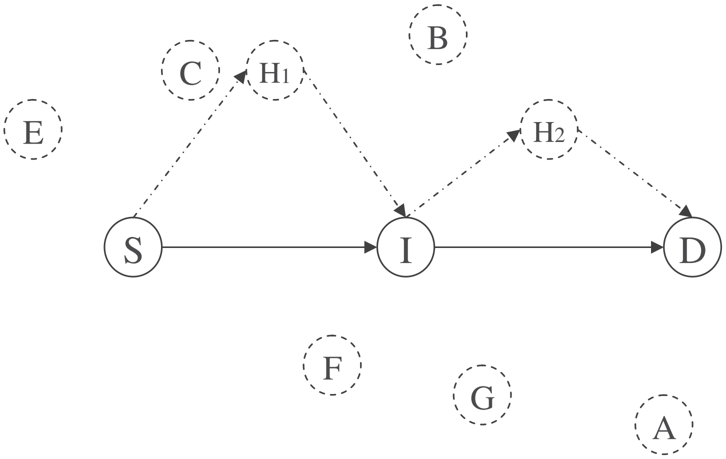

Figure D.1: An example of wireless mesh backbone.

is used to exchange resource request among one-hop and two-hop neighbors and allocate resources based on specific strategies. In addition to a small portion of the slot time, the control part is further partitioned into several small parts, called mini-slots, indexed sequentially with numbers 1, 2, 3, ..., m, 0, where m is the total number of routers in a two-hop neighborhood. The data part is dedicated for data packet transmission and dynamically distributed among routers according to the packet transmission allocation assigned by the control part. The Call For Cooperation (CFC) segment is used to send out the cooperation request, if necessary, and it is executed only if the direct transmission fails. We assume that the transmission of CFC packet is error-free.

In the wireless mesh backbone, mini-slots are assigned to each router with a mini-slot index in a cluster to allocate channel resource. In this study a cluster indicates the routers within the two-hop neighborhood of a router. Additionally, we use one bit as the status value of each mini-slot to indicate whether the channel is occupied or not, as shown in Fig. 2, where ”0” means that the channel is idle while ”1” indicates that the channel is occupied. The mini-slot index indicates the channel is occupied by which router[1] , and mini-slot 0 is reserved for cooperative communication. Within one slot, at most one mini-slot is allowed to have its status as ”1”. All mini-slots are emptied with ”0” if CFC is received in the previous slot.

B. Mini-slot Allocation

The mini-slot allocation has the following requirement: 1) Any two routers

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[1] The mini-slot status is set by a busy tone signal. It is sent out by the router with a low data rate in order to cover two-hop neighbors.

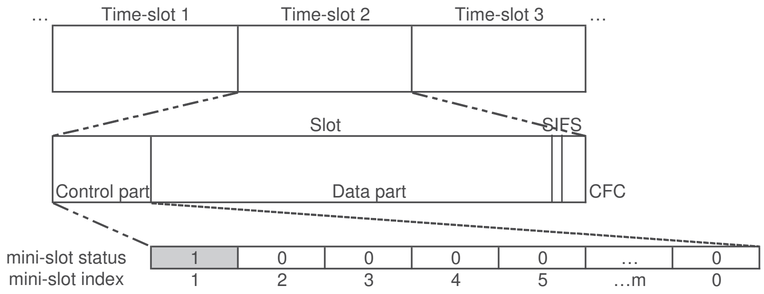

Figure D.2: Time-slot and mini-slot structures.

which are within the two-hop neighborhood of each other will not be assigned the same mini-slot; 2) The number of mini-slots should be minimum as a constraint for requirement 1) [24]. These two requirements can be implemented by graph coloring. From the graph theory a graph $G = (V,E)$ is defined with a set of vertices V and a set of edges of E connecting the vertices in a way that loops and multiple edges between vertices are forbidden. A vertex coloring for the graph G is a map $s : V(G) \rightarrow F$, where F is a set of colors. The coloring is permissible only if $s(V_i) \neq s(V_j)$ for all V_i and V_j that are two-hop away from each other. For the optimal coloring, the size of the color set should be minimum.

The mini-slot allocation can be mapped to graph coloring. If we want to optimally assign mini-slots to a set of routers $\{V_i\}$, an interference graph $G = (V,E)$ can be considered. The vertex set V is mapped to the set of routers $\{V_i\}$. The set of edges E consists of the vertices $\{V_k, V_l\}$, corresponding to the routers V_k and V_l that will interfere with each other within a two-hop neighborhood, should be assigned with different mini-slots. Eventually, the set of colors, F, corresponds to the collection of mini-slots for the routers. The mini-slot allocation task is resolved by coloring of G with the color set F. More details of the algorithm can be found in [18].

Considering that the routers in a wireless mesh network have no mobility and form a static topology, the mini-slot allocation algorithm is able to be performed by each router at the initialization phase of the network. Therefore, all the mini-slot allocations are pre-defined and known to all the routers.

C. The Cooperative MAC Scheme

In our scheme, cooperation is employed only if it is needed. Since cooperative relaying needs channel reservation for source, destination, and relay, it is often combined with medium access protocols. The proposed MAC scheme efficiently allocates all required channel resources by answering the following questions:

- How does a router reserve the channel and which router will reserve the channel first?
- When a router is allocated to a time slot, how to prevent other routers from using this slot?
- How to carry out cooperative transmission when the direct transmission fails?
- Which router would be selected to forward the packet if there are multiple relay nodes available?
- How does routers' transmission order rotate in the mini-slots after each transmission?

To better explain the proposed MAC scheme, a simple example is introduced to illustrate the operation procedure. As shown in Fig. D.3-(a), a two-hop network composed of routers S, I, and D is considered, and for simplicity there exists another router between each pair, which could be the potential relay. i.e., H1, H2. Assume that there is a flow transmitted from S to D, and relay H1 helps to forward the packets in the first hop if the direct transmission from S to I fails. After that, each router will follow the same principle to forward the packets to the final destination.

A basic rule for the MAC scheme is that *a router can transmit in a time slot when all the mini-slots prior to its own mini-slot are idle*. For instance, when a router (e.g. router S assigned with mini-slot i) starts a communication attempt, it firstly monitors all the mini-slot status from 1 to $i-1$. If "1" is detected at any mini-slot, the router will defer its transmission at the current slot. Otherwise, it means that all other routers within two hops from S which have been assigned mini-slots 1 to $i-1$ have no packet to transmit. Router S will then set its status value as "1" to reserve the channel and correspondingly transmit the packet at the data part of the same slot.

In the initialization phase, all the status of mini-slots is set to "0". Then the router with the smallest index of the mini-slot will reserve the channel first. The mini-slot allocation is shown in Fig. D.3-(b), where router S is assigned to mini-slot 1, router I is assigned to mini-slot 2, and so on. After the initialization of the mini-slot allocation, router S will set the mini-slot value as "1" at mini-slot 1 because it has the smallest index and therefore will get priority to reserve the channel. As a consequence, routers I, D, H_1 and H_2 will detect "1" at mini-slot 1, indicating that the channel is occupied at mini-slot 1. Then they will defer their transmissions at slot 0. Consequently, router S sends its packets at the data part of the same slot

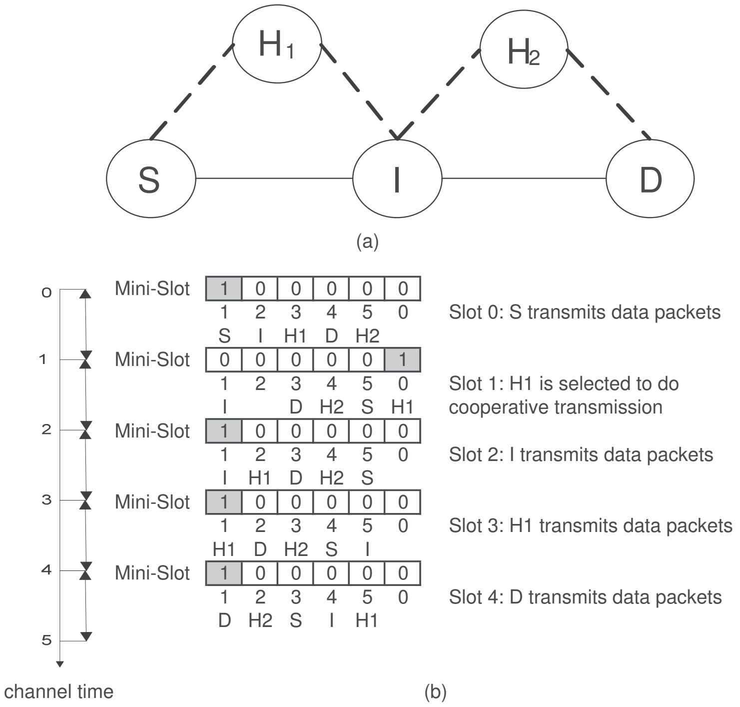

Figure D.3: An example to illustrate the operation procedure of the proposed MAC scheme.

without collision.

When router I receives the data packet, it will check if the packet can be decoded correctly or not. If the router fails to decode the packet, CFC will be sent out immediately at the CFC part of the current slot. The direct transmission is regarded as successful if no CFC packet is sensed. The CFC packet not only indicates that the received data packet is corrupted but also informs relays to initiate cooperative communication. Meanwhile, the mini-slot scheduled in the next time slot will be frozen (i.e., the mini-slot status is reset as ”0”) by the CFC packet because it is sent as a broadcast message. The transmission priority is given to the relay node rather than the node in the original schedule.

Next, we discuss how to do cooperation by the optimal relay node without interfering with other existing transmissions. Mini-slots reserve the medium for all the transmissions including both direct transmission and cooperative transmission, where mini-slot 0 is reserved for cooperation. As shown in Fig. D.3-(b) in the example, since the neighbors have already received and stored the overheard packets at slot 0, they will attempt to forward the packets to the intended router at slot 1 after sensing the CFC packet. The optimal relay will acquire the channel by means of a timer-based optimal relay selection algorithm which is implemented in a distributed manner at each node. The details of the optimal relay selection algorithm will be presented in the following section.

Since the router with small mini-slot index will always have priority to transmit packets, the router with largest index may starve. In order to allocate channel resource to each router in a fair manner, the transmission order of each router will rotate after each transmission. More specifically, the second mini-slot in the current slot will become the first one in the next slot, and the first mini-slot in the current slot will become the last one in the next slot, and so on. For instance, originally, router S gets the opportunity to transmit at slot 0 according to the rotation. After that, router I would seize slot 1 to transmit packet. However, since priority has been given to cooperative transmission, slot 1 will be allocated by relay H_1. The original mini-slot schedule is frozen by sensing the CFC packet, i.e., only mini-slot 0 is active and the associated router could transmit while other routers should give up their transmissions. The schedule will be activated after the cooperative transmission finishes. As shown in Fig. D.3-(b), at slot 2, router I catches the smallest mini-slot index, mini-slot 1, and it will transmit its packet at this slot. In case there is no packet to transmit at a router, e.g., H_1 in slot 3, it will keep silent and leave the transmission chance to the next router. Thus, the data parts of all the time slots are fully utilized as long as at least one router has packet to transmit. As a consequence, fair access and efficient channel occupation among all routers can be achieved.

V. RELAY SELECTION SCHEME

A. Optimal Relay Selection

In the section above we mentioned that the optimal relay is determined by a timer-based relay selection algorithm. In case there exist more than one relay nodes around each transmitter-receiver pair (i.e., the S-I link and the I-D link), the packets sent out from these relay nodes may corrupt each other if they transmit in the same time interval. In order to avoid packet collision, we select only one optimal relay in our cooperation scheme.

For cooperative transmission, each relay is connected with two channels, i.e., the channel from the source node to the relay node and the channel from the relay node to the destination node. In general, the cooperative benefits from relay nodes depend on both channels. If one of the channels corrupts, the relay cannot successfully forward the packet. Therefore, we apply the following criterion to select the relay: among all these relay nodes, the optimal one is selected according to the relay whose worse channel has the best link quality.

$$SNR_{opt} \Leftrightarrow max\{SNR_i\}, i \in [1,n] \Leftrightarrow max\{min\{SNR_{si}, SNR_{id}\}\}, i \in [1,n], \tag{1}$$

where n is the number of relays available for the transmitter-receiver pair; SNR_{si} and SNR_{id} are the link conditions in terms of received Signal to Noise Ratio (SNR) from source to relay and from relay to destination respectively. The relay i with maximal SNR_i is the optimal one. This scheme is able to balance the signal strength of these two links. The diversity gain of this scheme is analyzed in [3] based on the outage probability.

B. Distributed Relay Selection Process

Whether or not the optimal relay could provide maximum benefits depends not only on the relay selection algorithm but also how it is implemented in the medium access control scheme. In the TDMA-based MAC scheme, there is neither handshake between each node to collaborate with nor a centralized node to decide which relay transmits first. We consider a timer-based relay selection process because of its distributed feature and no feedback during the process. Each relay sets its own timer T_i such that the timer of the node with largest SNR_i expires first.

$$T_i = \frac{SNR_{threshold}}{SNR_i} m T_{ms}, \tag{2}$$

where $SNR_{threshold}$ is the SNR threshold to guarantee that the channel is in a good condition. Only relays with $SNR_i \geq SNR_{threshold}$ are qualified as the candidate for optimal relay. T_{ms} is the time duration of one mini-slot. It means that the timer of the eligible relay should expire within the time interval of all m number of mini-slots. Note that mini-slot 0 is not included in this interval. In other words, the optimal relay should be selected before the data transmission part of the same slot, as shown in the relay selection process in Fig. D.4, where T_{ctrl} is time duration of the total number of mini-slots with $T_{ctrl} = (m+1)T_{ms}$.

In [3], if there is no enough time for the second optimal relay to freeze its transmission when its timer also decreases to 0, it is possible that the packet sent out from the optimal relay would collide with the packet sent out subsequently by the second optimal relay. Additionally, potential collision caused by the packet from a relay which is hidden from the optimal relay may also occur. In our scheme, by means of the busy tone signal incorporated in the mini-slot design, those potential collisions could be avoided. More specifically, after the timer expires, the optimal relay will send out a busy tone signal to reserve the status of mini-slot 0 as ”1” instead of sending the data packet immediately. Then the rest of relays will freeze

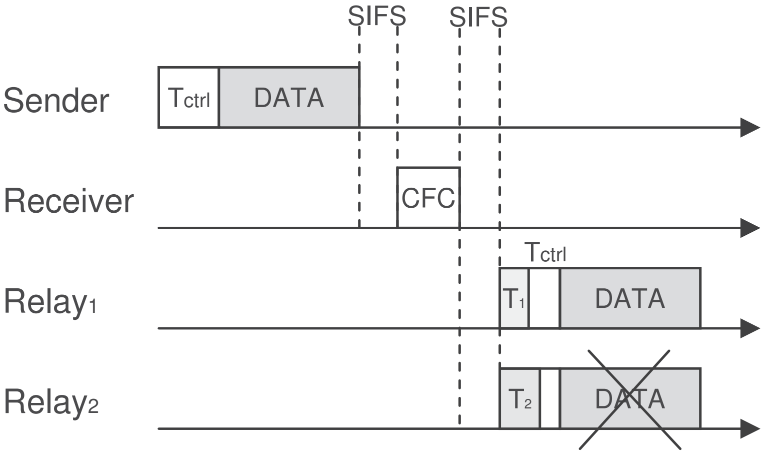

Figure D.4: Relay selection process.

their timers after they sense the status of mini-slot 0 as ”1”. Consequently, after all the mini-slots elapse, the optimal relay could transmit its packet with collision free. If none of the relay nodes expires within the time interval $m \cdot T_{ms}$, i.e., no qualified relay node is available in the network, the mini-slot 0 will keep status as ”0”. Then the source node will try to retransmit the packet. On the other hand, if the packet transmitted by the optimal relay is not successfully decoded at the destination, another CFC packet will then be sent out to initiate another round of cooperative transmission till the packet is correctly received.

The benefits of the proposed scheme is not only that the collision could be efficiently avoided but the relay selection time which is generally not negligible could also be finished within the inherent time of the system, i.e., control mini-slot time. Relay selection time in this study is defined as the interval from the time the relay nodes receive the CFC packet to the instant it starts to send the data packet.

The operations of the cooperative MAC protocol at the source, relay and destination nodes are illustrated in Fig. D.5-D.7, respectively. Note that all these three flow charts need to be implemented in any mesh router and the router may execute one of these procedures according to its role in each transmission, as the source, the relay, or the destination node.

VI. PERFORMANCE ANALYSIS

Since three channels have impact on the system performance, we model each channel as a two state discrete time Markov process. As system throughput is contributed by both direct transmission and cooperative transmission, we derive transmission

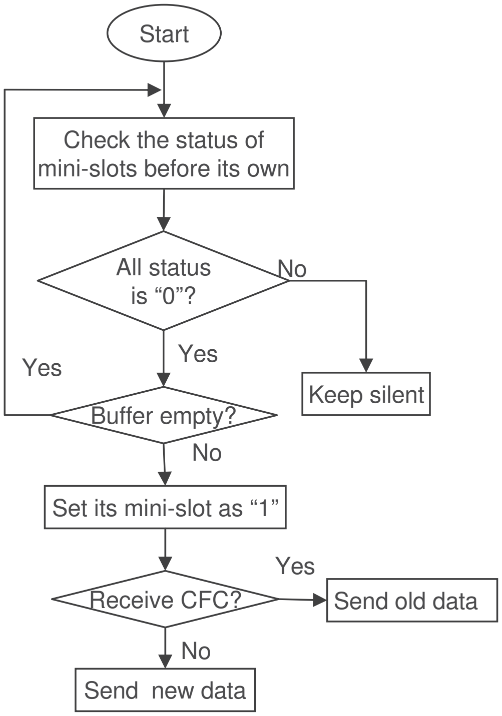

Figure D.5: Flow chart at source node.

efficiency of the proposed protocol based on another Markov model.

A. Channel Model

The transmitted signal is sampled once in each packet transmission, and it is assumed that the channel does not significantly change in this period. In fact, the channel characteristics used to compute the performance of the protocol at higher layer should reflect the physical layer characteristics to make these results meaningful. In this study, a two-state discrete time Markov process is considered to illustrate the sampled process of packet transmission over wireless channels, as shown in Fig. D.8. If the received signal is above certain threshold ? during the transmission time, the channel is regarded as in an ”on” state. Otherwise, it is categorized as in an ”off” state. The packet is assumed to be decoded correctly by the receiving router in the ”on” state, but not in the ”off” state.

In [6, 27], it has been observed that for a Rayleigh fading channel, the transition probability of the two state Markov chain can be expressed as

$$y = \frac{Q(\theta,\rho\theta) - Q(\rho\theta,\theta)}{e^{\Delta}-1}, \quad x = \frac{1-e^{-\Delta}}{e^{-\Delta}}y, \tag{3}$$

where $Q(\cdot,\cdot)$ is the Marcum Q function, $\theta = \sqrt{\frac{2\Delta}{1-\rho^2}}$, $\rho = J_0(2\pi f_m T_f)$, and $J_0(\cdot)$ is

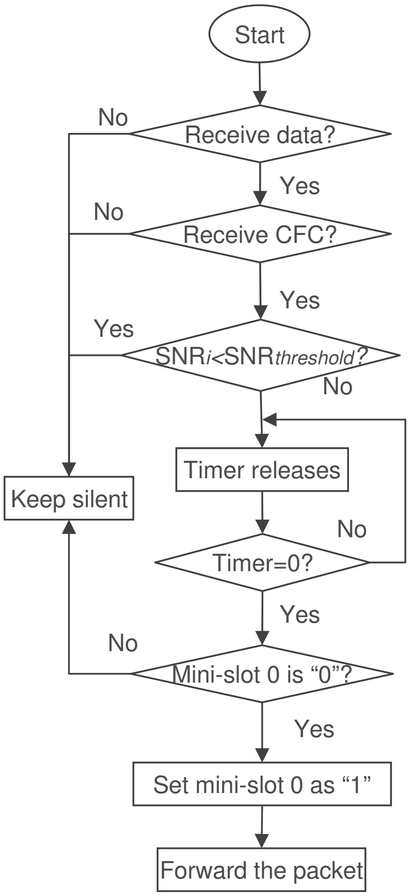

Figure D.6: Flow chart at relay node.

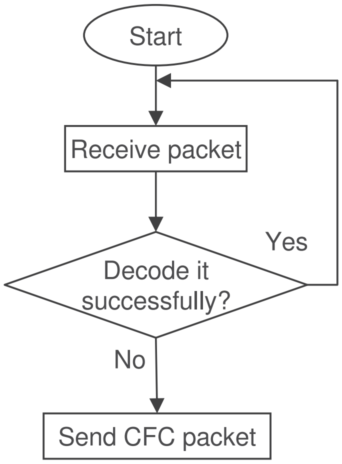

Figure D.7: Flow chart at destination node.

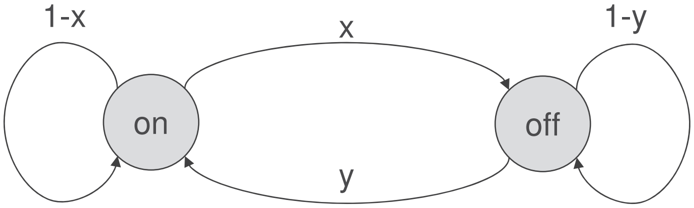

Figure D.8: Markov model for transmission process over wireless fading channels.

the zero order Bessel function of the first kind. In addition, the packet error rate in the direct link is defined by the ratio between the sum of dropped packets and the total number of packets transmitted. According to the channel properties, it is possible to find the probability that a packet is in error during the direct transmission, given by

$$\varepsilon = \frac{x}{x+y}. \tag{4}$$

Intuitively, we could obtain the probability of the packet transmission being successful as $1-\varepsilon$, which is defined as throughput efficiency.

B. Transmission Model

Since in each time slot of the proposed MAC protocol, either direct transmission or cooperative transmission is executed, it is possible to model this process by using another two-state Markov chain as shown in Fig. D.9. The parameters of this Markov model are defined as

$$p \triangleq P\{M(k)=C|M(k-1)=D\}, \;\; q \triangleq P\{M(k)=D|M(k-1)=C\} \tag{5}$$

where $M(k)$ denotes the transmission mode of the protocol, either direction transmission (D) or cooperative transmission (C). $M(k)$ will transit between the two states according to the transmission logic[2] of the protocol described in Table D.1, with the corresponding state transition probability matrix $\mathbf{V}(16\times16)$. We assume that there always exist relay nodes in the network to prepare for cooperation. As mentioned in the above section, if the packet transmitted by the relay node is not successfully received at the destination node, another cooperation will start. The next transmission mode of the system depends on both the states of three current channels and the current transmission mode. For example, when the current transmission mode is D, the transmission mode in the next state is only influenced by the direct channel in the current state other than the relay channels. As shown in the Table, from the row S_8 to S_{11}, $M(k)$ becomes C because the direct channel is

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[2] This logic (or transmission order) in M(k) is the cooperative transmission policy designed in our protocol which takes the status of all three channels in two consecutive slots into account.

”off”. Then the direct transmission will fail and cooperative transmission would be initiated in the next state. Similarly, when the current transmission mode is C, the next transmission mode relays on both the current direct channel and relay channels. Either direct channel or both two relay channels are ”on” the transmission could be successful. On the contrary, when the direct channel is ”off”, that one of the relay channels is ”off” would lead to transmission failure. The cases like in the row S_0, S_1, and S_2.

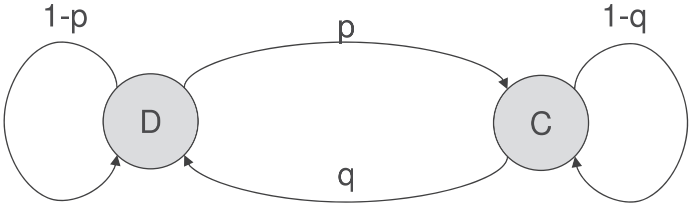

Figure D.9: Markov model for time slot.

Table D.1: State transition logic for time slot allocation

$\{M(k-1), Ch_{SD}(k-1), Ch_{SH}(k-1), Ch_{HD}(k-1)\}$	$M(k)$
$S_0 : \{C, off, off, off\}$	C
$S_1 : \{C, off, off, on\}$	C
$S_2 : \{C, off, on, off\}$	C
$S_3 : \{C, off, on, on\}$	D
$S_4 : \{C, on, off, off\}$	D
$S_5 : \{C, on, off, on\}$	D
$S_6 : \{C, on, on, off\}$	D
$S_7 : \{C, on, on, on\}$	D
$S_8 : \{D, off, off, off\}$	C
$S_9 : \{D, off, off, on\}$	C
$S_{10} : \{D, off, on, off\}$	C
$S_{11} : \{D, off, on, on\}$	C
$S_{12} : \{D, on, off, off\}$	D
$S_{13} : \{D, on, off, on\}$	D
$S_{14} : \{D, on, on, off\}$	D
$S_{15} : \{D, on, on, on\}$	D

Knowing the transition probabilities, we can calculate the steady state probability. The vector is expressed as $\mathbf{S} = [S_0, ..., S_{15}]$, where S_i is the steady state probability of each state in Table D.1. The vector can be obtained by solving the equations given by

$$\mathbf{S} = \mathbf{V} \cdot \mathbf{S}, \tag{6}$$

and the sum of all the probabilities would follow

$$S_0 + ... + S_{15} = 1. \tag{7}$$

By solving Eqs. (6) and (7), we can get all state probability S_i, for $i = 0, ..., 15$. Then the parameters of the two-state Markov model for the transmission mode can be obtained by

$$p = \frac{S_8 + S_9 + S_{10} + S_{11}}{\sum\limits_{i=8}^{15} S_i}, \quad q = \frac{S_3 + S_4 + S_5 + S_6 + S_7}{\sum\limits_{i=0}^{7} S_i}. \tag{8}$$

Therefore, the throughput efficiency of the cooperative scheme can be obtained as

$$\alpha = \frac{q}{p + q}. \tag{9}$$

C. System Throughput

In this section, we analyze the performance of the proposed cooperative MAC protocol in terms of system throughput. The normalized system throughput, denoted as η, is defined as successfully transmitted payload bits per time unit.

$$\eta = \frac{E[G]}{T_{frame}}, \tag{10}$$

where $E[G]$ is the number of payload information bits successfully transmitted in the time interval, and T_{frame} is the expected time interval which is known as the frame duration in the proposed TDMA system. In this study, $E[G]$ is contributed by two kinds of transmissions, i.e., direct transmission and cooperative transmission, respectively. Therefore, $E[G]$ can be expressed as

$$E[G] = uL(1 - P_e^D) + uLP_e^D(1 - \prod_{j=1}^{w} P_e^{C,j}) \;\; w \geq 1, \tag{11}$$

$$P_e^{C,j} = 1 - (1 - P_e^{si})(1 - P_e^{id}), \tag{12}$$

where L is the packet length; P_e^D is the Packet Error Rate (PER) of direct link; $P_e^{C,j}$ is the PER of the cooperative transmission at the j attempt, and w is the cooperative transmission attempts; P_e^{si} and P_e^{id} are the PER of the link from the source to the optimal relay and the link from the optimal relay to the destination, which could be obtained from the physical layer modulation scheme [10, 11]. Note that for each cooperation round, the optimal relay might be different; u is the number of packets transmitted in the direct link during the frame time. Note that among u number of packets, $u * P_e^D$ out of u direct packet transmissions failed. Thus, these packets need to be retransmitted in the cooperative link. However, the total transmission time of these data packets should be smaller or equal to the frame duration. It is clear that u satisfies the following function, and we select the largest integer value of u for throughput calculation.

$$T_{frame} \cdot \frac{T_{slot} - T_{ctrl}}{T_{slot}} \geq \begin{cases} \lceil u\frac{L}{R_D} + uP_e^D T_{C,1} \rceil, & w = 1 \\ \lceil u\frac{L}{R_D} + uP_e^D (T_{C,1} + \sum_{j=2}^{w} T_{C,j} P_e^{C,j-1}) \rceil, & w \geq 2, \end{cases} \tag{13}$$

$$T_{C,j} = \frac{L}{R_{C,j}} + T_{CFC} + SIFS, \tag{14}$$

where $\lceil \cdot \rceil$ is the ceiling function, T_{slot} is the slot time duration; T_{CFC} is the transmission time of CFC, $SIFS$ is the duration of SIFS silence period, R_D is the effective payload transmission rate for direct transmission, and $R_{C,j}$ is the transmission rate for cooperative transmission at the j attempt.

VI. PERFORMANCE EVALUATION

To evaluate the performance of our proposed cooperative MAC protocol, we have developed a network simulating program by using Matlab. We define a communication area ($500m \times 500m$) and three nodes are set along the center of the area in a two-hop route with an equal distance d between each node as illustrated in Fig. D.3. In every transmission, potential relay nodes are randomly generated to connect each source and destination pair. The channels among each node are modeled as i.i.d. Rayleigh fading channel. In general, with the same transmit power, the better the channel condition, the higher the received power. The received power P_{rx} when the pass loss coefficient between the two communication nodes is three and the reference distance d_o=1 meter is shown in the following equation.

$$P_{rx} = P_{tx} + 20log_{10}(\frac{\lambda}{4\pi d_o}) + 30log_{10}\frac{d_o}{d}, \tag{15}$$

where P_{tx} is the transmit power. In this paper, we consider four modulation schemes as BPSK, QPSK, 16QAM and 64QAM in terms of 802.11a specification. The modulation is adaptively changed according to the received SNR at the receiver, and the corresponding data rates are 6, 12, 36 and 54 $Mbps$. The threshold of modulation is calculated by satisfying that the BER is 10^{-5}. The threshold is given by Table D.2.

The noise level is assumed to be $-95\ dBm$. The other configuration parameters of the proposed protocol are summarized in Table E.1.

Table D.2: Threshold for adaptive modulation

Modulation	Threshold SNR
BPSK	6.8 dB
BPSK-QPSK	9.8 dB
QPSK-16QAM	16.5 dB
16QAM-64QAM	22.4 dB

Table D.3: Configuration parameters

Parameter	Value
Mini-slot duration	9 μs
Slot duration	1.6 ms
Frame duration	16 ms
SIFS	16 μs
DIFS	34 μs
CFC	14 $bytes$

Two scenarios are considered in the simulation. Firstly, we focus the scenario on one-hop transmission. Then, the benefit of flexible extension to a multi-hop transmission by the proposed protocol is illustrated by obtaining the end-to-end throughput gain in a two-hop transmission manner. For presenting our simulations we refer to our mini-slot based cooperative TDMA scheme as MS-C-TDMA in all these figures. In comparison, we illustrate the performance of the CSMA/CA, original TDMA and CoopMAC [14] schemes, together with ours.

A. Throughput Efficiency

To observe the impact of the channel condition on the transmission performance, throughput efficiency with different signal thresholds of the direct channel is investigated in Fig. D.10 by plotting Eqs. (4) and (9), respectively. It reveals that by decreasing the threshold of signal strength, which means the receiver has much more powerful signal processing capabilities, the probability of losing a packet decreases, leading to higher throughput efficiency. As the threshold of the signal to decode packets correctly increases, the relative channel condition decreases and more packets suffer from errors. In this case, cooperative transmissions are required to help deliver packets to the final destination. In other words, throughput derived from cooperative transmission could compensate the total throughput efficiency for all curves. It is observed that the participation of cooperation could greatly improve the communication performance in all range of signal thresholds. Particularly, if the signal threshold of the relay channels to decode packet successfully is always low (-4 *dB* in the figure), which means the relay channel is always good, the obtained throughput efficiency could be maximized. The benefit is much more evident when the signal threshold of direct channel is high.

While channel condition has great impact on transmission performance, system throughput also depends on the overhead of MAC layer and layers above. Therefore, we further evaluate the performance of the proposed cooperative MAC protocol in the next subsection.

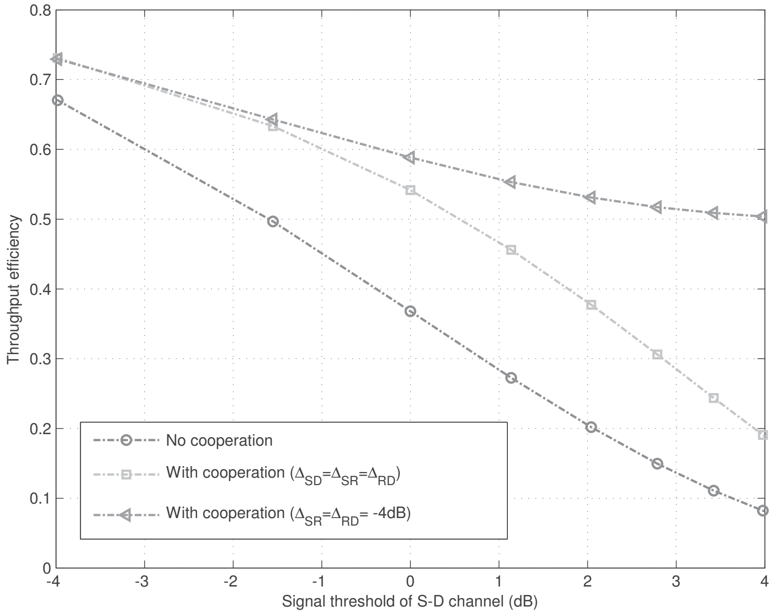

Figure D.10: Throughput efficiency vs. different signal threshold.

B. System Throughput

In Fig. D.11, we compare the throughput performance of these four schemes against link error rate of the direct channel. It is observed that as long as the direct link suffers from errors, MS-C-TDMA could provide higher throughput than that of CSMA, TDMA and CoopMAC schemes. The higher the error rate, the better the throughput improvement. This is because that the proposed scheme could provide priority access to cooperative transmission, ensuring channel access to the router which has better channel condition. In case there is slow fading in the direct transmission channel, the channel might remain in deep fading for long time with channel correlation (several data packets transmission time), hence retransmission from source router may not help in this case. As excepted, cooperative transmission from the optimal relay could most potentially help eliminate this problem.

Meanwhile, compared with CoopMAC, the throughput improvement of MS-C-TDMA is not only from the cooperative transmission but also due to that it is able to efficiently schedule the nodes to utilize the channel resource. Moreover, it can avoid packet collision, which is a main reason for system performance degradation of contention-based MAC schemes, such as the IEEE 802.11. Since the overhead caused by control mini-slots is much smaller than that caused by the backoff and RTS/CTS control messages, significant control overhead reduction in the proposed scheme is achieved.

Additionally, in a traditional TDMA system, channel reservation for all transmissions may lead to a situation of over-reservation. If a router does not have a packet to transmit during the time slot, this slot remains idle, i.e., the slot becomes wasted. However, in our proposed scheme the mini-slot design could efficiently schedule each transmission to guarantee the channel is fully utilized at the cost of only a small portion of the total slot time. If the current router with mini-slot status as ”1” has no packet to transmit, the router corresponding to the next mini-slot will quickly initiate a new transmission. Therefore, the control mini-slot based scheme could improve channel utilization, and this benefit can be translated into throughput improvement.

C. Transmit Power

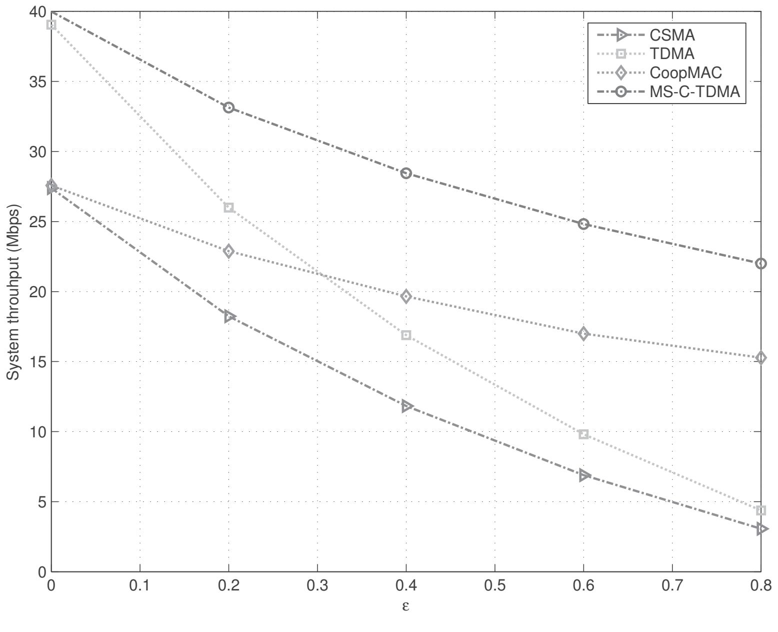

Figure D.11: System throughput vs. direct channel error rate.

Fig. D.12 shows the system throughput performance of the four schemes with the transmit power from -10 *dB* to 15 *dB*. As shown in the figure, the MS-C-TDMA scheme consistently outperforms the other two conventional schemes, and the gap becomes more significant when the transmit power is low (from -10 *dBm* to 5 *dBm*). This is due to the fact that lower transmit power will lead to less reliable transmission and cooperative diversity is fully exploited by cooperative transmission in this case. In this range the selected relay could provide better channel quality compared with the direct link. For instance, with the transmit power of -5 *dBm* MS-C-TDMA could obtain throughput of 26 *Mbps*, while the CSMA and TDMA schemes get merely 12 *Mbps* and 17.6 *Mbps* respectively.

In addition, MS-C-TDMA enhances the throughput more significantly than that of CoopMAC. That is because the elaborate design of the proposed MAC protocol could greatly reduce the MAC layer overhead. Each node could transmit the packet in its own time slot without packet corruption. Besides, with the contribution of cooperative transmission by the optimal relay node, system throughput could always be enhanced significantly when the direct link suffers from channel fading. Moreover, the relay selection time could be regarded as negligible as protocol overhead.

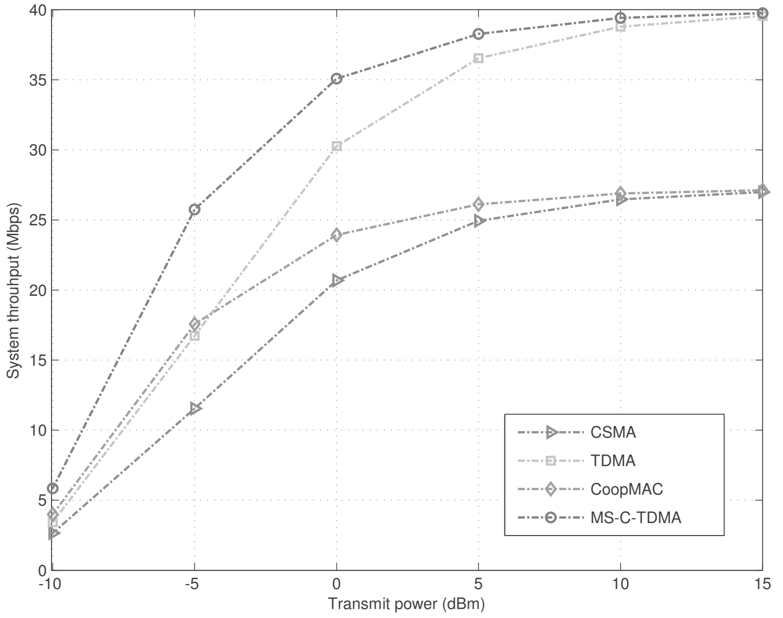

Figure D.12: System throughput vs. different transmit power.

D. The effect of payload Length

As known, payload length has major impact on the efficiency of a MAC protocol. To illustrate the advantage of the proposed scheme we exhibit the impact of packet length on system throughput. It is observed in Fig. D.13 that compared with other schemes, the proposed scheme performs more stable as the packet length varies.

It is clear that the throughput of CSMA scheme increases as the packet length grows. The reason behind this is that as the packet length increases the portion of data packet in the total transmission increases correspondingly, resulting in higher transmission efficiency. CoopMAC also agrees with the similar observation. In the TDMA-based scheme, a fixed number of data packets are transmitted for given packet length and transmission rate during the frame time duration. When the data rate is fixed in one frame, the larger the packet length, the smaller the number of packets. However, without heavy control overhead, like RTS/CTS, TDMA could obtain almost stable throughput when the payload length varies. Note that as the packet length becomes larger, the probability that packet transmission suffers from fading also increases, resulting in more transmission failures. That is why the curve of TDMA throughput decreases slightly when the payload length becomes larger. However, the proposed MS-C-TDMA scheme could efficiently alleviate this problem because of cooperative transmission. Therefore, MS-C-TDMA could achieve more stable throughput.

E. Throughput Gain versus Per-hop Distance

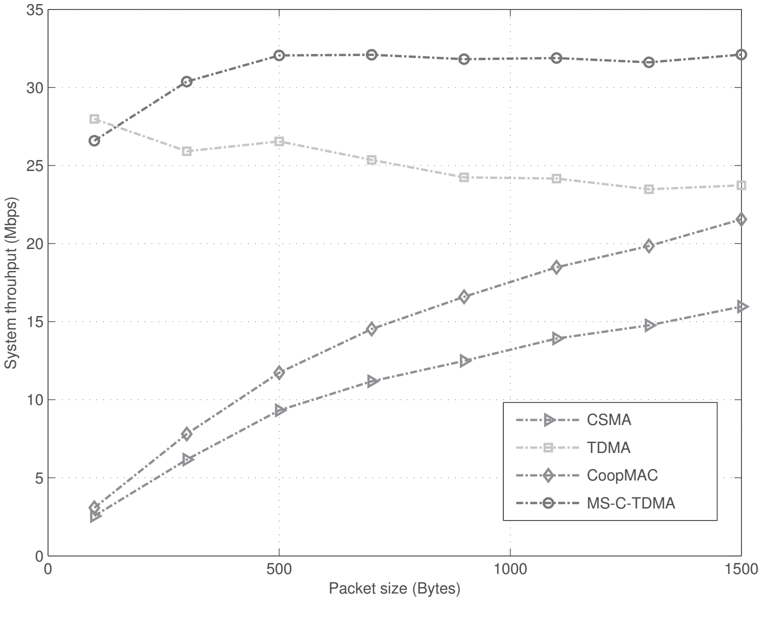

Figure D.13: Throughput vs. packet length.

In this subsection, we evaluate the system performance of the protocol where the per-hop distance d between the source node and the destination node varies from 30 m to 130 m. Fig. D.14 shows the throughput gain of the proposed MS-C-TDMA protocol over the original CSMA scheme. It is observed that as the per-hop distance increases, the throughput gain of cooperative schemes increases while conventional TDMA scheme keeps almost stable throughput gain. More specially, MS-C-TDMA outperforms CoopMAC in all ranges of distance. The increment of the throughput gain by MS-C-TDMA is larger than that of CoopMAC.

The reason is due to the fact that as the transmission distance is increased the throughput of the non-cooperative schemes is decreased correspondingly, while the performance of cooperative schemes is only degraded slightly. More specifically, with a short distance, the CSMA scheme could maintain stable delivery ratio. Therefore, cooperative transmission may not help a lot in this case. However, as d increases, the link is not robust that the frame error rate rises correspondingly. Then the benefit of cooperative transmission becomes convincing. Compared with one-hop transmission with low data rate, two-hop transmissions with high data rate by the cooperative transmission provide significant throughput gains. Note that nodes have to compete to access the channel at each hop when the contention-based scheme is applied. Therefore, with collision free in the two-hop cooperative transmission by MS-C-TDMA, the achieved increment of throughput gain is higher than that of CoopMAC. For instance, when the distance is equal to 50 m, the original scheme could obtain throughput of 17.4 $Mbps$. And CoopMAC could achieve 21.3 $Mbps$ while MS-C-TDMA is able to attain 34.3 $Mbps$. Therefore, the throughput gain by MS-C-TDMA is 1.97, which is larger than 1.22, obtained by CoopMAC.

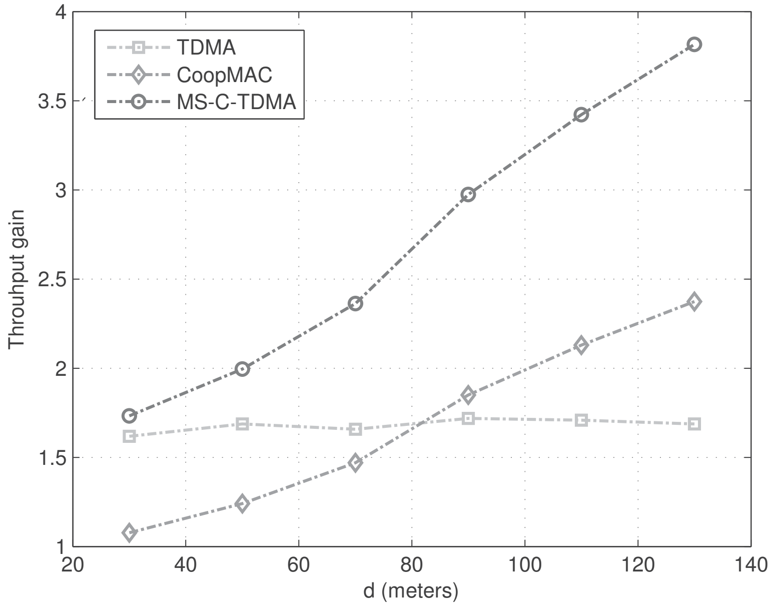

Figure D.14: Throughput gain vs. per-hop distance.

F. End-to-End Throughput Gain versus Network Density

Another advantage of the proposed scheme comes that it could feasibly extend the transmission from one-hop to multi-hop scenarios. In this subsection, we evaluate the performance of the proposed MS-C-TDMA in a two-hop transmission manner. Fig. D.15 illustrates the end-to-end throughput gain against CSMA scheme as network density rises.

Since the proposed scheme combats against packet collision and poor efficiency of the spatial reuse, the obtained end-to-end throughput gain by our proposed scheme is larger than 1. In addition, the curves depict that significant improvement is achieved by MS-C-TDMA as network density increase from 0.1 to 0.45. This feature is attributed to the fact that as the number of nodes increases in the communication area, the probability of successful cooperative transmission increases. However, further increasing networking density does not help for achieving higher throughput gain. In fact, a flat throughput gain curve is observed when network density is around 0.5. This can be explained as in a high dense network, large number of two hop neighbors corresponding to the same number of mini-slots will bring non-ignorable overhead. In that case, our solution may not be able to give such significant improvement.

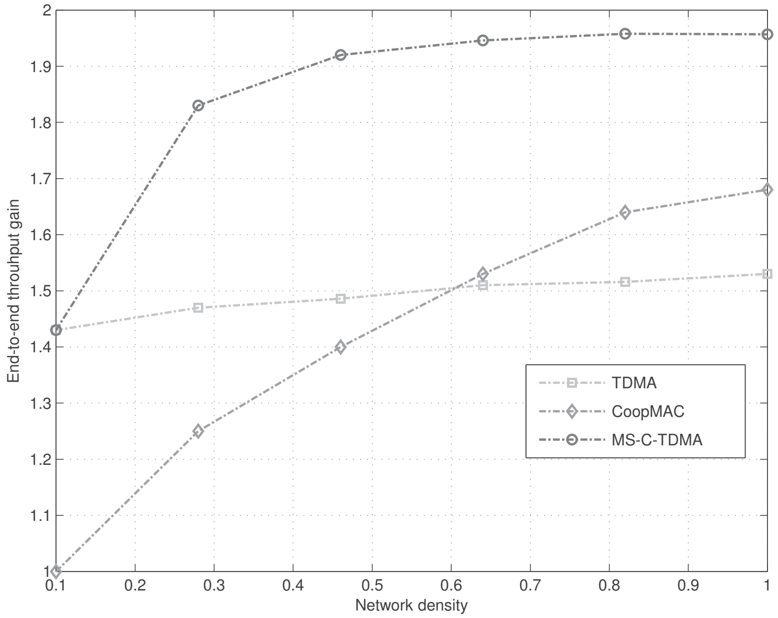

Figure D.15: End-to-end throughput gain vs. network density.

V. CONCLUSION

In this paper, we have presented a novel TDMA based multiple access scheme to facilitate cooperation in wireless mesh networks. With the help of mini-slots, channel resources are efficiently allocated to mesh routers in a distributed manner and higher priority has been given to cooperative transmission which is performed through an optimal relay. The optimal relay node is selected based on the combined instantaneous relay channel conditions. The effectiveness and the efficiency of this novel MAC scheme have been demonstrated with respect to system throughput, throughput gain in one-hop and two-hop scenarios respectively by considering several factors such as signal threshold, channel error rate, transmission power, hop distances, and network density. The obtained numerical results demonstrate that the proposed scheme is able to improve system performance significantly. This study could provide helpful insight to the development and deployment of cooperative communications for future broadband wireless mesh networks.

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E A Cooperative Lifetime Extension MAC Protocol in Duty Cycle Enabled Wireless Sensor Networks

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Title:	A Cooperative Lifetime Extension MAC Protocol in Duty Cycle Enabled Wireless Sensor Networks
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A Cooperative Lifetime Extension MAC Protocol in Duty Cycle Enabled Wireless Sensor Networks

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***Abstract* — To reduce energy consumption in wireless sensor networks, the concept of duty cycle is used in many MAC protocols. Although these protocols provide efficient energy-conservation solutions, they cannot resolve the energy hole problem in a multi-hop network, where a few nodes near the sink must relay the packets from the rest of the network, and consequently exhaust their batteries earlier. The previously proposed REACT forwarding protocol triggers the cooperation of several nodes to extend transmission range and hop over the highly burdened node, thereby allowing it to save its energy and extend the lifetime of the network. However, the previous work lacked a MAC protocol with a duty cycle. In this paper, we propose a novel cooperative duty cycle MAC (CDC-MAC) protocol, by employing a wake-up rendezvous selection scheme for multiple sensor nodes to exchange messages and a cooperator recruiting mechanism that favors nodes with more residual energy than the highly burdened node. Simulation results demonstrate that CDC-MAC can prolong the entire network longevity efficiently in comparison with another duty cycle MAC protocol, OC-MAC.**

I. INTRODUCTION

In multi-hop wireless sensor networks (WSNs), energy consumption is one of the most critical concerns, since recharging or replacing the exhausted batteries of sensor nodes is usually costly. Therefore, a primary design principle is not only to reduce the energy consumption of sensor nodes but also to avoid the exhaustion of a single node in order to prolong the entire network lifetime. Here, network lifetime is defined as the time when the first sensor has depleted its energy.

Duty cycle medium access control (MAC) has been proposed as an effective mechanism to extend the lifetime of WSNs, in which sensor nodes turn their radio on and off periodically to save energy. Duty cycle MAC protocols mainly fall into two categories: synchronous and asynchronous protocols. Synchronous approaches such as S-MAC [12] and DW-MAC [8], typically make sensor nodes wake up at the same time for data exchange. However, these types of protocols require precise synchronization, which causes more control overhead. On the other hand, in asynchronous duty cycle MAC protocols, such as RI-MAC [9], each node falls asleep and wakes up following its own schedule independently. Although such protocols reduce energy consumption, they may introduce significant latency in packet delivery, since a node with a packet to transmit must keep awake until its targeted receiver becomes active. Generally speaking, which protocol is more appropriate mainly depends on the network and application requirements.

However, these approaches in the current literature are still not sufficient to deal with the energy hole problem in multi-hop WSNs, in which the nodes around the sink are more heavily burdened than the others because they must relay packets to and from the rest of the network. These heavily burdened nodes consume energy at a high rate and deplete early since the data collected from the sensors is usually gathered at the sink. To cope with this problem, cooperative transmission (CT) with the benefit of range extension has been proposed to avoid the energy hole [5]. CT provides the spatial diversity benefits of an array transmitter, enabling a significant signal-to-noise ratio (SNR) advantage in a multi-path fading environment [6]. The Residual Energy Activated Cooperative Transmission (REACT) forwarding protocol in [5] triggers a CT when a node on a primary route to the sink determines through control packet exchange that it has higher residual energy than the next-hop node on the route. The node then recruits cooperators to transmit copies of the packet through independently fading channels, to extend the range and therefore hop over and protect the heavily burdened node. While [5] demonstrated that this approach shows significant promise, it assumed a highly idealized MAC protocol and it did not consider duty cycling. The objective of this paper is therefore to propose a realistic synchronous duty cycling MAC to support the CT operation in REACT. To our knowledge, there is no previous work about duty cycling in networks that also do CT.

Cooperative transmission works only when there are multiple active neighboring senders. Successful transmission of the necessary control messages and copies of the data is extremely challenging when the duty cycles are asynchronous. OC-MAC [11] is an asynchronous duty cycle MAC considering a different kind of cooperation between active senders. However, this cooperation scheme focuses merely on how nodes can help each other to relay packets rather than addressing cooperative diversity. In this paper, we propose a multiple wake-up provisioning cooperative duty cycle MAC protocol (CDC-MAC), which aims to balance the energy consumption of distributed nodes from the entire network point of view by exploiting cooperative diversity gain. CDC-MAC employs a receiver-initiated approach to establish wake-up rendezvous between sender, receiver and cooperator(s). More specifically, when the residual energy difference is detected, neighboring nodes are allowed to exchange data and do cooperative transmission directly towards a two-hop-away receiver. In this way, the energy-bottleneck node could avoid depleting its battery early, resulting in prolonged network lifetime, since energy consumption is evenly balanced across the network. The performance of CDC-MAC is evaluated by simulations.

The remaining part of this paper is organized as follows. The network model and protocol design consideration are presented in Sec. II. In Sec. III, we present CDC-MAC design in details. Then the system performance is evaluated and compared with other duty cycle MAC protocols in Sec. IV. Finally the paper is concluded in Sec. V.

II. NETWORK MODEL AND PROTOCOL DESIGN CONSIDERATION

In a typical WSN, multiple data flows converge towards a single point or sink, constructing a tree topology. Correspondingly, routing protocols in WSNs normally form a collection tree. For instance, the default routing protocol in TinyOS 2.x is the collection tree protocol, in which one or more nodes in the network declare themselves as the sink node(s) and all other nodes in the network recursively form a routing tree [2]. As shown in Fig. E.1, a number of sending nodes, like C, D, E etc, will transmit packets to Node A via Node B. Since Node B needs to help other sensors to forward packets, it would consume more energy. When the consumed energy at Node B exceeds certain threshold, an energy hole is formed. No matter how much residual energy is left in the rest of the network, it becomes disconnected due to this energy hole.

To keep the network alive, one solution is to perform transmission with longer distance which could jump over the heavily burdened node and reach the two-hop away node directly. Transmission range extension can be achieved through cooperative transmission by forming a virtual multiple-input-single-output (MISO) transmission [3, 6], which was demonstrated experimentally in [4]. However, to perform CT in a duty cycle WSN, it is necessary to ensure that the corresponding nodes are active at the same time interval for data transmission. In this case, synchronous duty cycle protocol is a better option since nodes can be synchronized to wake up at the same time period.

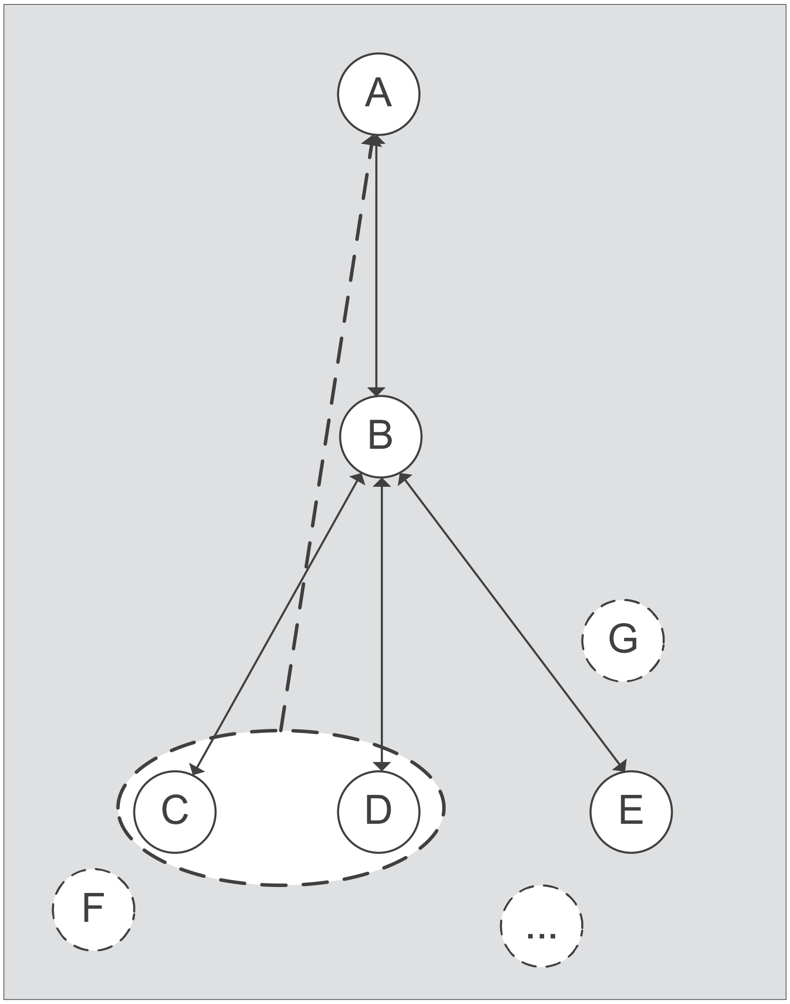

Figure E.1: Network model for CT to overcome energy hole.

III. CDC-MAC DESIGN

In this section, we describe the basic principle of CDC-MAC. We also discuss the main goals and challenges of integrating cooperative transmission into a duty cycle MAC protocol.

A. Rendezvous Selection for Data Transmission

Similar to DW-MAC [8], CDC-MAC is a synchronized duty cycle MAC protocol, which assumes that the network synchronization is implemented by a separate mechanism during the Sync period. The basic idea of CDC-MAC is to schedule the involved sensors, including the sender, the receiver and the cooperator(s), to wake up at the same period when there are packets to transmit. It employs a receiver-initiated procedure with multiple wake-ups in a cycle to establish rendezvous for exchanging data among them.

CDC-MAC utilizes a Sync packet initiated by the receiving node, e.g., Node B in Fig. E.1, to schedule and synchronize the other nodes in its vicinity. More specifically, CDC-MAC works in two phases as described below.

Phase I) *Network initialization and rendezvous*: before initialization, each node has its own wake-up pattern. To initiate synchronization with other nodes, Receiver B wakes up at its scheduled time sending a Sync message to potential senders as a beacon, as shown in the upper part of Fig. E.2. Other senders, e.g., C or D in the same figure, follow their original wake-up patterns during a cycle. Once waked up, a node scans the network and remains active until a Sync message is received. When Sync is captured, it sends an ACK to B, acknowledging the reception of the Sync message. When this procedure is completed, a sender is locked to a specific wake-up interval for its data transmission in Phase II. For example, $w_{B,1}$ is locked as the transmission rendezvous for Node C to communicate with B. Note that a sender may keep awake for almost one wake-up interval of B (e.g., $\frac{1}{4}$ of T_{cycle} for Node D in Fig. E.2) in order to receive Sync, but when the transmitting and receiving nodes are synchronized, the active window size of the transmitter will be decreased significantly. For next cycle, each node follows the new wake-up and sleep schedules. For example, Node B establishes the transmitting rendezvous at A's wake-up period $w_{A,1}$ with Receiver A, and at its own wake-ups $w_{B,0}$ and $w_{B,1}$ with Nodes C and D respectively, as shown in Fig. E.3(a).

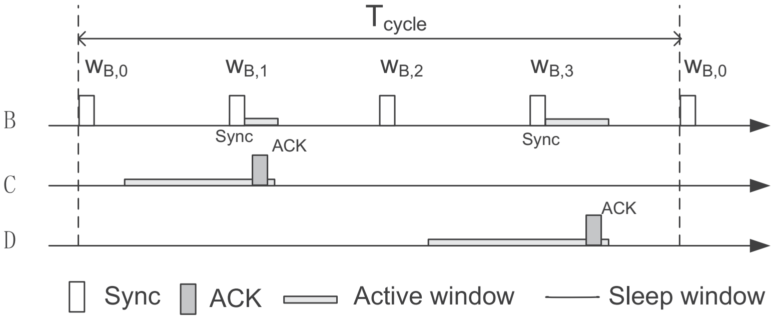

Figure E.2: Phase I: Network initialization.

Phase II) *Data transmission*: For data transmission, two requirements are considered: 1) to ensure that the corresponding nodes in the CT group store their selected rendezvous and wake up at the same rendezvous in the duty cycle; and 2) to minimize energy consumption and transmission delay. When a regular or non-CT transmission is performed, as shown in Fig. E.3(b), Nodes C and D will adhere their transmissions to B during the same wake-up period which was originally assigned to C (how this is performed will be explained in the next subsection) as the first hop transmission. B will then forward these packets to A at A's immediate wake-up period $w_{A,1}$ as the second hop transmission. Otherwise, the second hop transmission has to be performed in the next cycle, incurring long delay. When cooperation transmission is needed, B, C and D will utilize B's wake-up period $w_{B,0}$ for cooperation handshake represented by the triangles under $w_{B,0}$ (more details in the next subsection). Then C and D will perform CT directly towards A over one hop represented by the rectangles under $w_{A,1}$ in Fig. E.3(c). In the same manner, nodes on different hops adaptively build up an almost synchronized data forwarding structure.

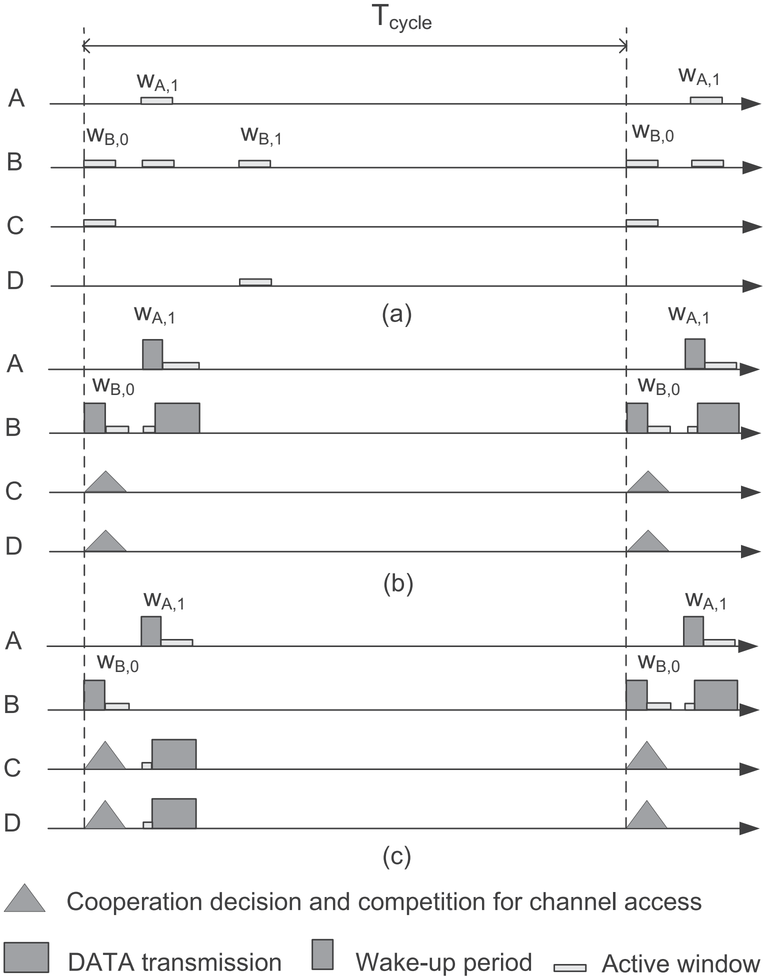

Figure E.3: (a) Synchronized multiple nodes in a duty cycle. (b) Non-cooperative transmission in a duty cycle with two hops, C/D→B at $W_{B,0}$, and B→A at $W_{A,1}$ respectively. (c) CT in a duty cycle with one hop, C/D→A at $W_{A,1}$.

B. Energy-Balance-Oriented Scheduling

In a single-channel WSN, packet collision may happen when multiple nodes try to access the shared medium at the same time. In this study, based on different considerations on node selection, we develop two variations of CDC-MAC, as CDC-MAC-I and CDC-MAC-II respectively. While nodes with pending DATA to send will apply *random backoff* scheme for channel access in CDC-MAC-I, CDC-MAC-II utilizes a distributed *timer-based* node selection scheme to select the CT initiator and cooperator(s) considering both individual node residual energy and load balancing among nodes.

Examples corresponding to the *Data transmission* phase in CDC-MAC including both regular two-hop transmission and direct cooperative transmission are illustrated in Fig. E.4 and Fig. E.5 respectively. These two figures provide zoomed-in details about the procedures that happen within the large rectangle or the triangle shown in Fig. E.3 (b) and E.3 (c) respectively. In the beginning of each triangle period, Node B sends a ready to receive (RTR) message to the sending nodes to initiate DATA communication, if the medium is sensed as idle. In addition to requesting for data transmission, the RTR message contains also its residual energy and distance information. Upon receiving RTR, the sending node, e.g., C, obtains the distance information between Node B and Node A, and between Node B and itself. It also derives the residual energy of the receiver. Comparing with its own residual energy, the sending node decides whether to do CT or not [4].

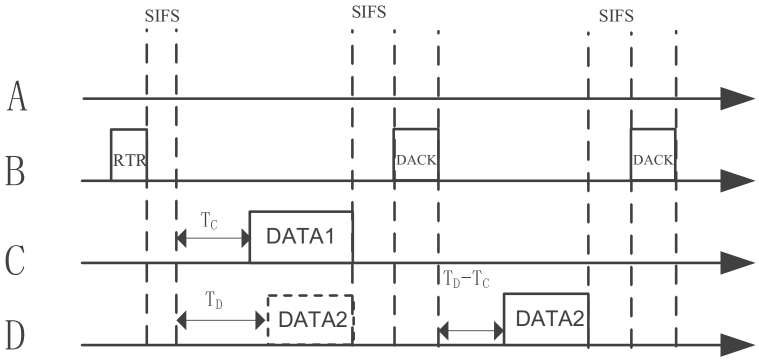

Figure E.4: Regular transmission within the same wake-up period.

CDC-MAC-I: As shown in Fig. E.4, Nodes C and D are both sending nodes. Each of them waits for a SIFS period after receiving the RTR message and then contends for channel access using a random backoff scheme. The dashed line packet indicates the node, e.g., D in Fig. E.4, that lost the competition. The node that captures the channel will send DATA to receiver B directly if its residual energy is lower than B's. Node B replies with DATA-ACK (DACK) when it receives DATA.

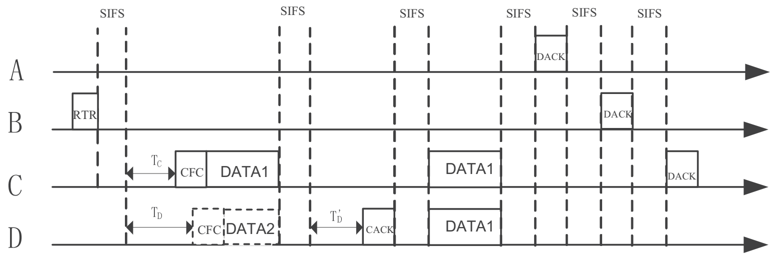

Figure E.5: CT within the same wake-up period.

In the meantime, other nodes which lose the previous contention will freeze their backoff counters. They resume counting to send DATA when the medium is sensed free again. On the other hand, *if the sending node which captures the channel has higher energy than the receiving node, it will initiate CT* by sending out a call for cooperation (CFC) message piggybacked with DATA. Assume it is Node C that first accesses the channel as illustrated in Fig. E.5. CFC is sent by C to recruit other nodes to initiate cooperative transmission. Additionally, it also contains residual energy information of Node B which is derived from the RTR message received by Node C. Meanwhile, the CFC message stores the information on how many cooperators are required for CT (how this number is determined is explained in the next subsection). Upon overhearing the CFC packet, the energy-bottleneck Node B will go to sleep and other node will compare its own residual energy with the received residual energy of Node B. Consequently, the nodes with their remaining energy above Node B's become cooperator candidates and they will store the overheard DATA message. After a SIFS, the cooperator candidate acknowledges Node C with cooperative ACK (CACK). Note that collision may happen if multiple candidates try to send CACK to the common Node C at the same time. Thus, another backoff scheme is required to avoid potential collision of CACKs.

In CDC-MAC-I, we still utilize the random backoff scheme to avoid CACK collision. When Node C receives enough number of CACKs as required in the CFC packet, it will prepare for CT. Nodes that are not participating in CT should update their network allocation vectors (NAVs) to reflect that the channel is busy for the duration specified in the message. Since CACK transmission with low data rate covers larger distance than the DATA transmission, we assume each candidate could overhear the CACK transmission of other cooperative candidates. When the required number of CACKs has been sensed, the candidate that has not sent its CACK yet will terminate its transmission. CT by Node C and the selected cooperators will then be concurrently performed [1] after another SIFS interval from the time that the last required CACK has been received. Once Node A receives the DATA packet sent through CT, it will respond with DACK to Node C over two hops, from A to B and then from B to C. Since DACK for CT will be sent back to Node C via Node B in the current cycle, Node B has to wake up again before the arrival of the DACK packet. Even though this procedure consumes energy to reactivate Node B, we can still conserve energy instead of keeping Node B always awake. In order to capture DACK sent from A, Node B needs to wake up at the instant $(2*DATA+CACK+DACK+3*SIFS)$ seconds after it goes to sleep, given the number of cooperators is 3. If CT fails by the default number of cooperators, retransmission of CT (reCT) will be initiated as described in the next subsection.

CDC-MAC-II: Although being able to avoid collision by random backoff, CDC-MAC-I does not consider the residual energy in the contention phase of sending nodes. Therefore, a timer-based sender selection scheme which relies on the residual energy of nodes is proposed as CDC-MAC-II. This scheme ensures that the most preferred node transmits first for both CT candidate selection and CACK collision avoidance. For regular transmission, it is not critical on which candidate node should access the channel first. However, *if the node with highest energy acts as the first sending node, CT will occur more frequently, consuming potentially extra energy of other nodes in the network*. This may happen if a random node is selected, e.g. as a result of the backoff scheme used in CDC-MAC-I. Considering that the node with least energy may concentrate on its own packet transmission rather than cooperation, it is preferred that this node accesses the channel first. Based on this observation, the node with least energy is considered as the most appropriate initiator for CT in CDC-MAC-II and will capture the channel first according to the following timer:

$$T_i = \lfloor \frac{V_i}{V_{max}} \Delta \rfloor, \tag{1}$$

where V_i represents the residual energy of node i, V_{max} is a constant, and $\lfloor \cdot \rfloor$ is the floor function. It is shown that nodes will transmit only at finite discrete time instants. The granularity of T_i could be configured flexibly. However, if the T_i values are too close to each other, the DATA message may also collide. On the other hand, if the T_i values are far away from each other, it will result in longer delay. Hence, we determine the granularity of T_i based on Δ, depending on an acceptable value of the collision probability [10].

Furthermore, when CT is initiated, another cooperator selection scheme needs to be performed in order to avoid potential collision of the CACK packets from cooperator candidates. To keep energy consumption balanced, selecting the node with higher energy as the cooperator could better balance the energy distribution in the network. Thus in CDC-MAC-II, the nodes with higher residual energy will be the preferred cooperators according to the following timer-based node selection scheme,

$$T_i' = \lfloor (1 - \frac{V_i'}{V_{max}'})\Delta' \rfloor. \tag{2}$$

As a result, the node whose timer first elapses to 0, will send CACK first. Consequently, the information on residual energy in the CFC packet is not necessary when CDC-MAC-II is employed. This decreases the complexity of the protocol.

C. Cooperator Recruiting Algorithm

Cooperative transmission in our MAC protocol forms a virtual MISO transmission, which has been demonstrated to be able to extend the transmission range [4]. In MISO techniques, range extension mainly depends on the number of cooperators, N_c, which determines the diversity gain. As concluded in [3], the cooperative diversity gain is monotonically increasing with N_c. However, if N_c is too large, the total energy consumption for performing CT would be noticeably high. Therefore, it is necessary to obtain an approximation of the number of cooperators on the basis of range extension factor. The range extension factor, β, is defined as the ratio between the cooperative transmission distance, d_{ct}, and the single-input-single-output (SISO) link distance, d_{non-ct}, i.e., $\beta = d_{ct}/d_{non-ct}$. For Rayleigh fading, β is given as [3],

$$\beta = 10^{(10log_{10}N_c + G(N_c))/10\alpha}, \tag{3}$$

where N_c is the number of cooperators, $G(N_c)$ is the cooperative diversity gain by N_c number of cooperators, α is the path-loss exponent, which is typically between 2 and 4. In the proposed algorithm, given the extension factor β we could obtain the approximation of N_c. Table I provides a few examples of N_c and β at a target Bit Error Rate (BER) of 10^{-3} [3, 5]. In order to avoid a complex calculation of the optimal number of cooperators using Eq. (3), which may also give extra burden on node energy consumption, each node could store this relationship or a similar

Table E.1: Diversity Gain and Range Extension (BPSK. BER=10^{-3}).

N_c	2	3	4	5	10
$G(N_c)(dB)$	10	13.5	14	14.5	15.9
$\beta(\alpha = 3)$	2.71	4.07	4.65	5.2	7.3

one as a lookup table. For example, if the required d_{ct} satisfies $d_{non-ct} < d_{ct} < 2.71d_{non-ct}$, we set the optimal number of cooperators, N_c^{opt}, as 2, and $N_c^{opt} = 3$ given $2.71d_{non-ct} \leq d_{ct} < 4.07d_{non-ct}$, and so on. In general, in order to further guarantee that the selected cooperators could help the sending node jump over the energy-bottleneck node, a cooperator candidate that has shorter distance to the two hop away receiver, i.e., A, in Fig. E.1, is preferred in CDC-MAC. However, adding more constraints on the selection criterion could induce a new problem that there are not enough candidates for CT. This tradeoff could be determined based on node density in a network.

Furthermore, cooperative transmission may not always succeed due to for instance the selected cooperators failed to provide the required range extension. If this happens, the sending node sets N_c as $N_c + 1$ and initiates reCT. Note that the goal of CDC-MAC is to protect the energy-bottleneck node so that it does not die earlier than the other nodes. Thus, a bound on the number of retransmissions would decrease the incidence of exhausting all participating nodes which in turn reduces the energy consumption in comparison with the traditional point-to-point MAC protocols. Therefore, if the number of reCTs exceeds a predefined limit, regular hop-by-hop transmission will be revitalized again.

IV. PERFORMANCE EVALUATION

To show the effectiveness of the proposed protocol, the simulation results for CDC-MAC and another point-to-point MAC protocol, OC-MAC, obtained by using a custom-built MATLAB simulator are illustrated in this section. The simulation topology is similar as shown in Fig. E.1. We assume that a number of sensor nodes are randomly deployed in a $500\ m \times 250\ m$ area. Node B is deployed at the center of the area while a sink node is randomly deployed in the upper part of the rectangle area. Other nodes are uniformly deployed in the lower part of the rectangle area. All sensor nodes except the sink independently generate packets and send them to the sink in a multi-hop manner. The channels between nodes are modeled as i.i.d. Rayleigh fading channels. In order to measure the energy consumption of the protocol, the transmission power of the nodes is set to be the same. We measure the amount of time the radio of each node has spent in different modes: sleep, idle, transmission, and reception. The energy consumption ratios for sleep:idle:reception:transmission are set as 0:1:1.05:1.4 [7]. The retransmission limit of CT is set as 3.

A. Lifetime Comparison of Different Protocols

Fig. E.6 depicts the lifetime comparison of these two protocols. We could observe that the lifetime of OC-MAC decreases linearly when the residual energy of node reduces. For the CDC-MAC protocols, when the residual energy is high, CDC-MAC-I demonstrates advantage with respect to lifetime. This is attributed to cooperative transmission that protects the energy constraint node. On the other hand, it is shown that CDC-MAC-II consumes energy at a higher rate when the residual energy of node is high. This is because that CT in CDC-MAC-II is usually performed when the energy-bottleneck node has lower energy, whereas hop-by-hop transmission is dominated at high residual energy range. Besides, in comparison with OC-MAC, extra synchronization in CDC-MAC needs to consume energy. However, from the network lifetime point of view (the first node depletes in the network), CDC-MAC-II has achieved maximum lifetime. The reason is as follows. When an energy hole is formed, CT in CDC-MAC-II is continually applied, which significantly extends the lifetime of the bottleneck node. In addition, selecting node with high energy as the cooperator balances the energy distribution in the network. However, protecting the energy constraint node by CT is achieved at the cost of consuming more energy on other nodes. Hence, overuse of CT may result in limited cooperator candidates later on, which in turn leading to limited lifetime extension, like CDC-MAC-I.

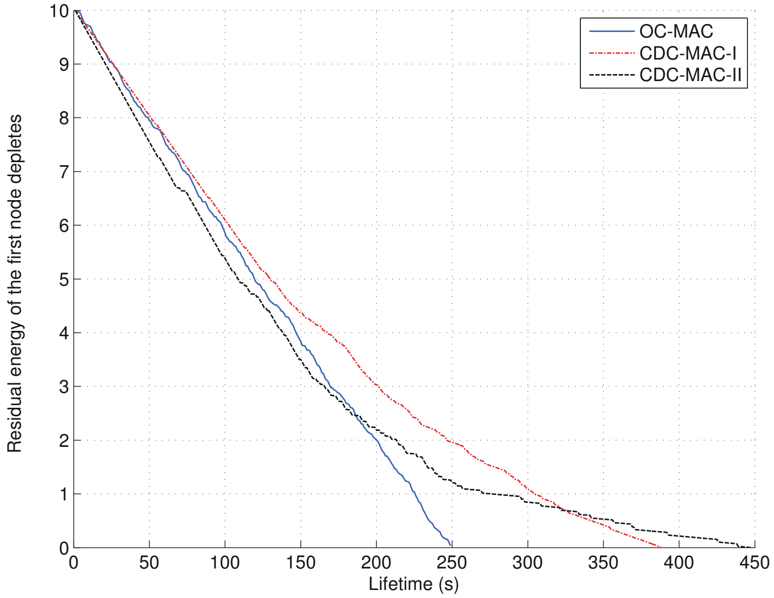

Figure E.6: Lifetime comparison of different protocols.

B. Balanced Network Lifetime

In order to further illustrate the merit of the proposed CDC-MAC protocols, we look at network lifetime from another angle by redefining network lifetime as the time that the last node drains its energy. In Fig. E.7, we find that Node B depletes much earlier than other nodes when OC-MAC is used. It results in network exhaustion in a realistic scenario wherein the other nodes that still have lots of residual energy would be wasted. This is because in OC-MAC there is no such CT mechanism that could help save energy of the energy bottleneck node. Node B is overused in OC-MAC even though it has pretty low residual energy. This situation could be changed by means of CT in the proposed CDC-MAC protocols. Since CDC-MAC-II exhibits advantage on network lifetime over CDC-MAC-I, we focus only on CDC-MAC-II, as shown in Fig. E.8. It is found that almost all nodes run out of energy at the same time. Therefore, in CDC-MAC-II, the energy of nodes could be fully and evenly utilized.

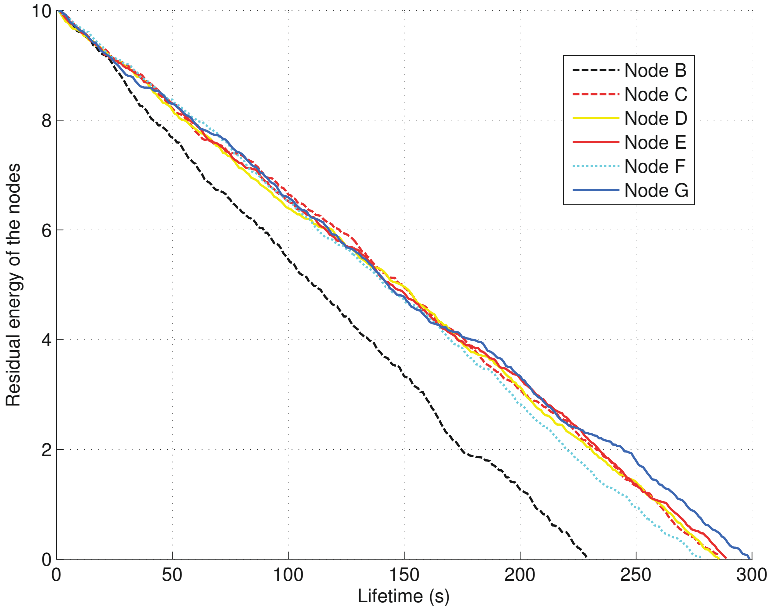

Figure E.7: Lifetime of each node in OC-MAC.

C. Cooperative Retransmission Probability

Since reCT consumes more energy, which may compromise the benefit of CT, we investigate the reCT probability of CDC-MAC. If CT is successful, for each successful CT the sum of probabilities of CT and reCT would be equal to 1. That is,

$$\sum_{i=0}^{n} P(Success/(Nc+i)nodes) = 1, \tag{4}$$

where $P(Success)$ denotes the probability of the event that the transmission succeeds, $P(Success/(N_c+i))$ is the conditional probability of successful transmission given retransmission by (N_c+i) nodes, and n is the number of retransmissions. In

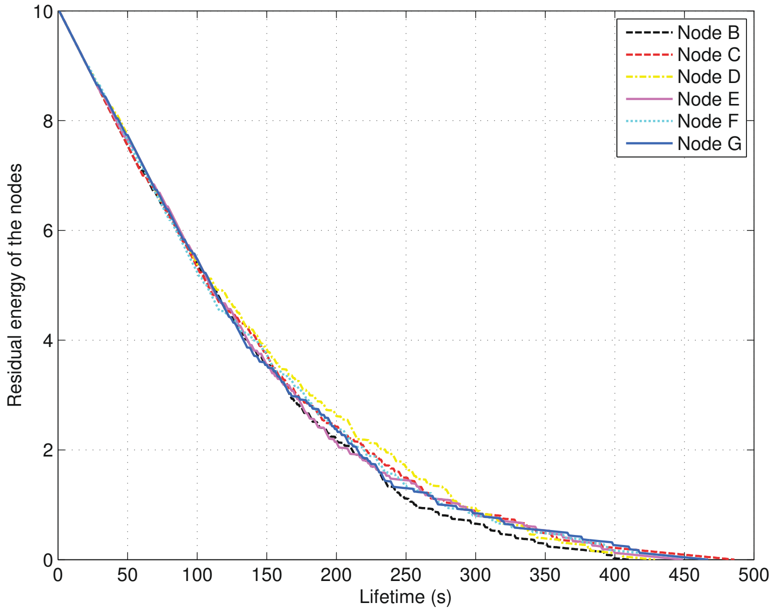

Figure E.8: Lifetime of each node in CDC-MAC-II.

Fig. E.9, reCT-i ($i \in [1,2,3]$) indicates retransmission times of CT. We could observe that CDC-MAC-II has higher successful cooperative transmission probability than CDC-MAC-I does, while CDC-MAC-I has higher reCT-3 than CDC-MAC-II. The main reason behind reCT is that the selected cooperator cannot provide enough diversity gain to transmit packet directly to the two-hop away receiver. For CDC-MAC-I, the situation is even worse. Random selection of sending node will result in a situation that this sending node may have higher energy than other sibling nodes. During CT initiated by this sending node, even though only the candidate that has higher residual energy than the energy-bottleneck node could be selected as the cooperator, it is still possible that there exist some nodes with lower residual energy than the energy-bottleneck node, leading to a limited number of qualified candidates. In CDC-MAC-II, as long as the neighbor nodes could hear the CFC packet, it is possible to be selected as the cooperator.

V. CONCLUSIONS

In this paper, a cooperative duty cycle MAC protocol CDC-MAC has been proposed to extend the network lifetime of WSNs. By exploiting the physical layer property that an increased transmission range can be achieved thanks to diversity gain, CDC-MAC schedules when necessary cooperative transmissions to protect the energy-constrained node. In this protocol, both distance information and residual energy

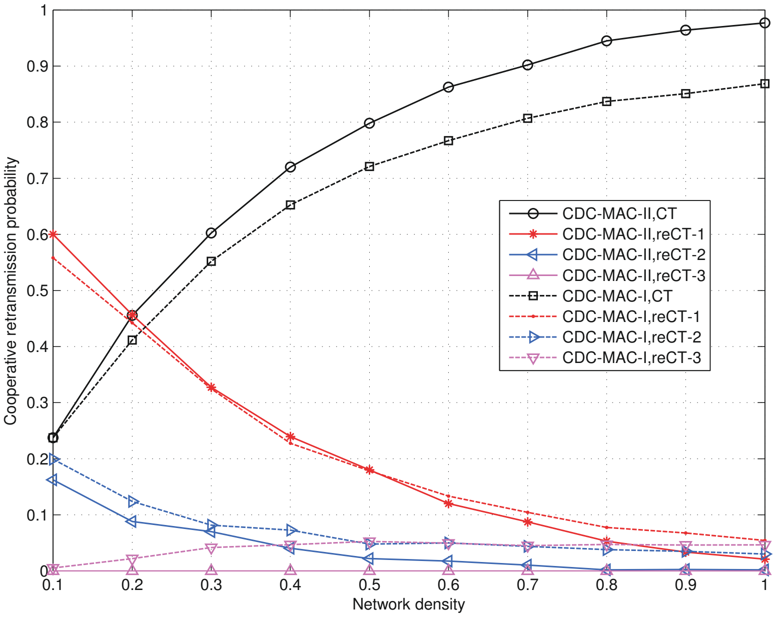

Figure E.9: Cooperative retransmission probability of CDC-MAC protocols.

information are taken into consideration to select the CT initiator and its potential cooperator(s). The simulation results demonstrate that the energy consumption levels of sensor nodes are evenly distributed in the network by using CDC-MAC, resulting in more balanced node transmission and energy resource utilization. As a consequence, CDC-MAC could provide significant network lifetime extension in comparison with traditional point-to-point duty cycle MAC protocols.

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