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Link-Layer Cooperative Communication in Vehicular Networks

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To my mother, Ambika, and my father, Murari—S.B.

To my sons, Alan and Alvin—W.Z.

Preface

Vehicular ad hoc networks (VANETs) are a special kind of communication networks, where vehicles communicate with each other and with stationary road side units (RSUs). VANETs are expected to support a large spectrum of mobile distributed applications that range from road safety applications to on-board infotainment applications. As communication nodes (vehicles or RSUs) are organized in an ad hoc manner to form a communication network, VANETs possess some special characteristics, such as the highly dynamic network topology (with high node mobility and frequent link breakage) and stringent quality of service requirement (for high priority delay sensitive safety messages), as compared with the general mobile ad hoc networks (MANETs). Hence, directly applying the existing communication protocols designed for MANETs may not be reliable and efficient in VANETs. Thus, investigation and development of VANET communication protocols are required to support the wide range of applications.

The objective of this book is to study three fundamental issues related to link-layer cooperation in VANETs: (1) how to utilize the available radio resources efficiently for more reliable transmission in the existing distributed TDMA[1] (D-TDMA) medium access control (MAC) protocols, (2) how to customize node cooperation mechanism such that it does not interfere with any D-TDMA operations, and (3) how to support safety-related applications which use broadcast services. Further, we present link-layer cooperative frameworks addressing these fundamental issues to improve communication quality in VANETs. We evaluate the performance of the proposed cooperation schemes with computer simulations and mathematical analysis in terms of throughput and transmission reliability. The proposed node cooperation frameworks enhance the performance of D-TDMA

[1]Time Division Multiple Access.

MAC, making it more robust to tackle dynamic networking conditions in VANETs and more suitable to support the wide range of applications and their strict service requirements.

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May 2017 | Weihua Zhuang

Contents

Acronyms

1PPS	One-Pulse-Per-Second
ACK	Acknowledgement
AU	Application Unit
C-ACK	Cooperation Acknowledgement
CAM-MAC	Cooperative Asynchronous Multi-channel MAC
CC-MAC	Coordinated Cooperative MAC
CCH	Control Channel
CD-MAC	Cooperative Diversity MAC
cdf	Cumulative Distribution Function
CDMA	Code Division Multiple Access
COH	Cooperation Header
CoopMAC	Cooperative MAC
CraSCH	Cooperative Reservation of SCH
CRB-HSCP	Cooperative Relay Broadcasting with Helper Selection Based on Channel Prediction
CRB-OPT	Cooperative Relay Broadcasting with Optimal Helper Selection
CRC	Cyclic Redundancy Check
CRT	Cooperative Relay Transmission
CSI	Channel State Information
CTS	Clear-to-Send
D-TDMA	Distributed Time Division Multiple Access
DIFS	Distributed Inter-frame Space
DSRC	Dedicated Short Range Communication
eCAH-MAC	enhanced Cooperative ADHOC MAC
EDCA	Enhanced Distributed Channel Access
FCC	Federal Communications Commission
FI	Frame Information
GPS	Global Positioning System
HGV	Heavy Goods Vehicle
i.i.d	Independent and Identically Distributed
IDF	Identification Field

ITS	Intelligent Transportation Systems
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MSD	Minimum Safety Distance
NACK	Negative Acknowledgement
OBU	On-board Unit
OHS	One-Hop Set
pdf	Probability Density Function
PH	Packet Header
pmf	Probability Mass Function
PN	Pseudo-random Noise
PTD	Packet Transmission Delay
QoS	Quality-of-Service
rDCF	Relay-Enabled Distributed Coordination Function
RSS	Received Signal Strength
RSU	Road Side Unit
RTS	Request-to-Send
$s-d$	A pair of source and destination nodes
SCH	Service Channel
SDMA	Space Division Multiple Access
SNR	Signal-to-Noise Ratio
TDMA	Time Division Multiple Access
THS	Two-Hop Set
Type-C	Cooperation Packet
Type-G	General Packet
Type-R	Reservation Packet
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad Hoc Network
WAVE	Wireless Access in Vehicular Environment
WBSS	Wave-Mode Basic Service Set
WSA	WAVE Service Advertisement

Nomenclature

$AC0$	Access Category 0
$AC1$	Access Category 1
$AC2$	Access Category 2
$AC3$	Access Category 3
E_1	Event that potential helpers exist for cooperative relay transmission
E_2	Event that unreserved time slots exist for cooperative relay transmission
E_3	Event that a contending node chooses an unreserved time slot among all the available unreserved time slots
E_4	Event that an unreserved time slot is not selected by contending nodes
F	The number of time slots per frame
G_r	Antenna gain at a receiving node
G_t	Antenna gain at a transmitting node
$I_v(\cdot)$	The v^{th} order modified Bessel function of the first kind
$J_0(\cdot)$	The zeroth-order Bessel function of the first kind
L	The number of lanes in a road segment
M	The packet transmission delay, in frames, in ADHOC MAC
M_{coop}	The packet transmission delay, in frames, in CAH-MAC
M_{max}	The maximum packet transmission limit
N_C	The number of contending nodes in a reference two-hop neighborhood
$N_T(\overline{N}_T)$	The (average) number of nodes in a reference two-hop neighborhood
N_o	The number of common one-hop neighbors of a pair of source and destination nodes
P_t	The constant transmission power of all nodes
P_{bb}	The probability that channel is in the *bad* state in the current time slot and remains unchanged in the next time slot

P_{gg}	The probability that channel is in the *good* state in the current time slot and remains unchanged in the next time slot
R	Transmission range of a vehicle
T	The number of frames per second
U	The number of failed time slots per frame
X	The number of successful time slots per frame
X_{coop}	The number of successful time slots per frame with cooperation enabled transmission
Y	The number of potential helpers for a given failed packet transmission
$\varDelta$	A fixed, and small, time duration
$\varGamma(\cdot)$	The gamma function
$\varGamma(\cdot,\cdot)$	The upper incomplete Gamma function
$\varOmega$	The packet dropping rate in ADHOC MAC
$\varOmega_{coop}$	The packet dropping rate in CAH MAC
$\varPhi_3(\cdot,\cdot;\cdot,\cdot)$	The confluent hypergeometric function
$\varPi_z$	The set of calculated probability of finding the channel in a *good* state from the perspective of node z
$\aleph$	The number of vehicles in the network
α	Path-loss exponent
β	The sum of time durations to sense the channel, transmission time of a cooperative acknowledgement, and the guard time
β_1	The time duration during which a destination node senses the channel before cooperative relay transmission
β_2	The transmission time of a cooperative acknowledgement plus the guard time
δ	A fixed number such that $\delta\varDelta$ is the time durations of a time slot minus the transmission time to perform cooperative relay broadcasting
δ_z	A random number that node z draws for black-burst before cooperative relay broadcasting
ϵ_A	The utilization of an unreserved time slot in ADHOC MAC
ϵ_C	The utilization of an unreserved time slot in CAH-MAC
ϵ_E	The utilization of an unreserved time slot in eCAH-MAC
η	The ratio of the number of reserved time slots in a frame to the total number of time slots per frame
$\gamma_r(\bar{\gamma}_r)$	The (average) received power by a node at a distance r from the transmitter
γ_{th}	Threshold received power level
$\mathcal{A}_{zx}$	The set of failed nodes, predicted and reported combined, that are in one-hop transmission distance from node x from the perspective of node z

$\mathcal{B}_x$	The set of all time slots which belong to two-hop neighbors of node x
$\mathcal{D}'$	The optimal set of potential destination nodes that received packet during a cooperative relay broadcasting
$\mathcal{D}$	The set of potential destination nodes that do not have the tagged packet
$\mathcal{F}$	The set of all time slots in a frame
$\mathcal{H}$	The set of potential helper nodes with the tagged packet
$\mathcal{K}$	The set of indicator variables (k_{xy}) indicating the transmission status from node y to node x
$\mathcal{M}_i$	A random variable representing the channel state during i^{th} time slot
$\mathcal{O}_z$	The set of all one-hop neighbors of node z
$\mathcal{O}_z^f$	The set of one-hop neighbors of node z that failed to receive the tagged packet
$\mathcal{O}_z^r$	The set of one-hop neighbors of node z that already reported its transmission status with a source node
$\mathcal{O}_z^s$	The set of one-hop neighbors of node z that successfully received the tagged packet
$\mathcal{O}_z^{crb}$	The set of one-hop neighbors of node z that already performed cooperative relay broadcasting
$\mathcal{P}_z^f$	The predicted set of one-hop neighbors of node z that failed to receive the tagged packet
$\mathcal{P}_z^s$	A predicted set of one-hop neighbors of node z that successfully received the tagged packet
$\mathcal{Q}$	The set of indicator variables (q_y) indicating the selection of node y as the best potential helper node
$\mathcal{R}_z^f$	The set of one-hop neighbors of node z that reported failure to receive the tagged packet
$\mathcal{R}_z^s$	A set of one-hop neighbors of node z that reported the successful reception of the tagged packet
$\mathcal{T}_z$	The set of all two-hop neighbors of node z
$\mathcal{V}$	The set of indicator variables (v_{xy}) indicating the channel condition from node y to node x
π_g	The steady state probability of finding the channel in the *good* state
π_g^{xy}	The steady state probability of finding the channel in the *good* state from the perspective of node z, when node x transmits a packet to receiving node y
ρ	The vehicle density of a road segment
ρ_i	The vehicle density of lane i
σ	The throughput of ADHOC MAC
σ_{coop}	The throughput of CAH-MAC

σ_{gain}	The normalized throughput gain achieved by cooperation in CAH-MAC over ADHOC MAC
τ	The duration of a time slot
θ	The slope value of effective velocity
ϱ	The amplitude correlation coefficient of a received signal
c	The speed of light
f_c	The carrier frequency of signals
f_d	The average Doppler spread
m	The shape parameter of a Nakagami-m channel
o	The offset value of effective velocity
p	The probability that a vehicle within the transmission range of a source node successfully receives the transmitted packet, taking account of a possible poor channel condition
$p(n,z)$	The probability of finding n vehicles along a road segment of length z
p_c	The probability of transmission collision in a given time slot
p_s	The probability of successful transmission between a pair of source and destination nodes during a reserved time slot
p_s^{coop}	The probability of successful transmission between a pair of source and destination nodes during a reserved time slot, with cooperation enabled transmission
p_{coop}	The probability of cooperation
v_r	The velocity of a receiver
v_t	The velocity of a transmitter
v_{eff}	The effective velocity between a receiver and the transmitter
w_l	The width of (each) lane l of the road

Chapter 1
Introduction

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The increasing number of road accidents and more frequent traffic congestion have resulted in the evolution of intelligent transportation systems (ITS) [6] and other mobile distributed applications which improve road safety, increase transportation efficiency, and provide on-board infotainment. On the other hand, the rapid advancement of wireless communication technology and automotive industries have led to the paradigm of vehicular ad hoc network (VANET) as a promising approach to provide a communication infrastructure supporting ITS and other on-board applications, primarily to improve road safety. In VANETs, vehicles are equipped with various onboard sensors, which gather information, and communication devices, which provide networking interface to exchange the gathered information through wireless medium. According to the National Highway Traffic Safety Administration (NHTSA) of the United States Department of Transportation (USDoT), traffic accidents, specifically unimpaired vehicle crashes, can be reduced by approximately 80% through the deployment of road safety applications enabled by VANETs [7]. In addition, comfort related applications such as gaming, automatic toll collection, drive-thru Internet connections, multimedia services are expected to be delivered to vehicles for their drivers and passengers, providing on-board infotainment services [8–10].

Motivated by its immense potential, several stake holders including governments, academia, and telecommunications and automotive industries have taken initiatives in developing VANETs, with various projects [11–16] focusing on designing protocols, algorithms, and systems for VANETs. In addition, several consortiums [17, 18] have been established to standardize the proposed protocols and algorithms. Furthermore, government agencies have come forward and allocated radio spectrum for VANETs. In the United State, the Federal Communications Commission (FCC) has allocated 75 MHz of Dedicated Short Range Communication (DSRC) spectrum in 5.9 GHz band [19]. Similarly, in Europe, one control channel and seven service channels each of 10 MHz have been allocated in 5.855–5.925 GHz band for vehicular communication [20]. Also, in Japan, a channel in 755.5–765.5 MHz

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for vehicular safety applications and 12 different channels in 5.770–5.850 GHz band for passenger entertainment and commercial applications have been allocated [21–24].

1.1 Vehicular Ad-Hoc Networks

VANETs are a special kind of mobile ad hoc networks (MANETs) in which vehicles are primary communication nodes, to facilitate a safe and efficient vehicle transportation system. In contrast to the general MANETs, VANETs may use the fixed stations (or stationary communication infrastructures) that are deployed along the roadside, referred to as road side units (RSUs). Figure 1.1 illustrates a simple network architecture of VANETs, where vehicles on the road can communicate with each other and/or with a stationary infrastructure along the roadside. Each vehicle is equipped with an on-board unit (OBU) and/or one or multiple application units (AUs) [25]. The OBU, a device with wireless networking interfaces, enables vehicles to communicate. The AUs, on the other hand, are devices which run application(s) and make use of the OBU to exchange information with other vehicles [25]. Thus, in VANETs, vehicles communicate with each other via vehicle-to-vehicle (V2V) communication and/or with stationary road side infrastructure via vehicle-to-infrastructure (V2I) communication, to exchange information generated by a wide range of mobile distributed applications.

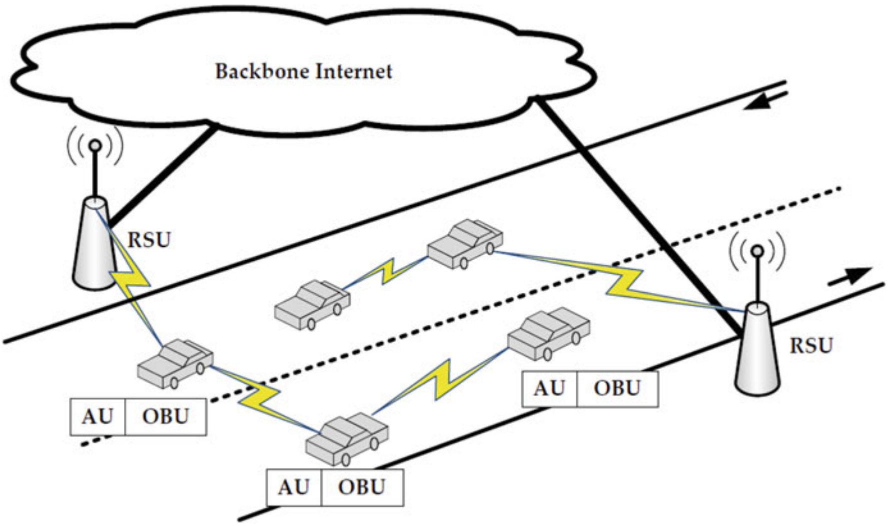

Fig. 1.1 An illustrative network architecture of a VANET

1.1.1 VANET Applications

Vehicles communicate via a radio channel to exchange messages to support a wide range of mobile distributed applications. Based on their objectives, these applications can be broadly categorized into the following three groups [9, 10, 26–31].

1. **Safety applications** to improve road safety: Providing warning messages to drivers regarding safety threats due to possible vehicles collision, road damage, weather condition, are some examples of safety applications;
2. **Traffic management applications** to increase the vehicle traffic efficiency: Navigating to an alternative route in case of a disaster or heavy traffic condition, avoiding and reducing vehicle congestions, and assisting a driver to find parking space, are examples of traffic management applications;
3. **Infotainment applications** to entertain or comfort drivers and/or passengers: In-vehicle Internet access, multimedia services, online gaming, video streaming, point-of-interest information, location-specific information/advertisements, and electronic flyer distribution can be considered under this category.

1.1.2 VANET Characteristics

VANETs have some unique characteristics as compared to other forms of wireless networks such as MANETs or cellular networks. The differences are mainly in terms of the network architecture (presence of direct transmission among stationary RSUs and highly mobile vehicles in the absence of a central controller), users mobility pattern (presence of highly mobile vehicles with restricted mobility guided by the geometry of roadways), energy constraints (presence of high capacity on-board batteries) and, finally, the presence of real-life applications [32]. Furthermore, the radio spectrum allocated for VANETs is divided into multiple channels as in DSRC, such that the control channel is used for broadcasting safety messages and control information, and negotiation between a pair of provider and user to run infotainment applications using the service channels (spectrum allocation of DSRC and multi-channel operations are discussed in Appendix A). Such differences result in both challenges and opportunities in the development and operation of VANETs. For example, the on-board batteries are capable of supplying sufficient energy and alleviate energy constraints on VANET applications and communication protocols. On the other hand, high node mobility and variations in vehicle speed and density in space (such as city, highway, and rural areas) and in time (such as holidays, rush hours) result in dynamic topology changes with frequent link breakage [33–36]. Moreover, a wide range of VANET applications impose diverse quality-of-service (QoS) requirements in its communication protocols. For example, most of the safety applications require a message[1] to reach 99% of the target destination nodes within 100 ms [30, 37, 38], i.e., high communication reliability and strict delay constraints [27, 39], which is difficult to guarantee due to the VANET dynamic networking conditions. A broadcast service helps to disseminate messages from a transmitting node generating the messages to its neighboring nodes [40]. Thus, the broadcast service is used by safety applications for disseminating messages to nodes within an area of interest, e.g., within one-hop transmission distance of a source node that is generating the messages. Hence, VANETs require an efficient, reliable and robust broadcast service to successfully deploy the safety applications with stringent QoS requirements. On the other hand, non-safety applications such as gaming and video streaming are throughput sensitive.

In order to develop a robust, efficient, and reliable communication protocol in VANETs, the aforementioned advantages should be exploited and the challenges must be addressed. One of possible ways to meet such challenges is by enabling node cooperation focusing on link-layer or medium access control (MAC) protocol design in VANETs.

1.2 Node Cooperation in Wireless Communication

The performance of wireless networks is affected by various channel impairments (such as fading, shadowing, path loss) and limited radio spectrum resources. Transmission diversity and channel coding are some common techniques which are deployed in the link-layer to mitigate the wireless channel impairments and to improve network throughput. However, these techniques may introduce some overhead or require multiple antennas and/or transceivers. On the other hand, cooperative communication (or node cooperation) emerges as an efficient alternative approach which makes use of nearby nodes to improve transmission performance between a pair of source and destination ($s-d$) nodes via diversity gain. Cooperative communication exploits the broadcast nature of a wireless transmission by relaying overheard messages when the direct transmission between an $s-d$ pair suffers from a poor channel condition. The overheard packet is relayed to the destination node by a node or nodes which have a good channel condition to both $s-d$ nodes. Such a node that performs cooperative relay transmission is referred to as helper node.

In a simple implementation, helper nodes relay a packet which failed to reach the target destination, improving the communication reliability. Figure 1.2 illustrates the basic functionality of cooperative communication, where communication between

[1]Safety messages can be either periodic or event-driven [30]. Periodic messages are generated periodically, normally 10 messages per second, and consist of information such as position, speed, deceleration, etc. On the other hand, event-driven messages are generated when some unexpected events occur, such as bad road condition, sudden lane changing, etc., to warn the nearby drivers about the events.

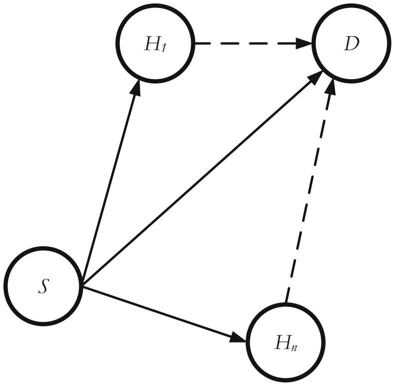

Fig. 1.2 Simple example of a cooperative communication

the source node S and destination node D can be boosted by multiple helper nodes, denoted by $H_1, \ldots, H_n$. There may be only one helper. In a case with multiple helpers, all the helper nodes relay the failed packet and the destination node D combines multiple signals from all the helpers in detection. A helper node is chosen based on parameters, such as the received signal-to-noise ratio (SNR), transmission data rates, success rate of the past transmissions, that reflect its channel conditions with the destination node. Cooperative relay transmission from the neighboring node(s) of an $s - d$ pair, the helper nodes, can enhance the throughput and transmission reliability of the entire network [41–44]. In this book, we focus on node cooperation frameworks on the link layer for VANETs to improve the system performance.

1.3 Motivation and Research Contributions

Traditionally, node cooperation for MAC protocols, also referred to as cooperative MAC protocols, in wireless networks have been proposed for faster transmission [45, 46], or to reduce the packet dropping rate [47]. Cooperation in the link-layer is done by the use of a suitable node which has good channel conditions to both source and destination nodes. Dynamic topology changes, high relative mobility among nodes, and frequent changes in vehicle density are some factors that impose challenges in VANETs, making the development of an effective MAC protocol extremely difficult. D-TDMA MAC, such as ADHOC MAC [48] and VeMAC [49], provides a collision-free broadcast service in VANETs with acknowledgement (ACK) from all the receivers within one-hop transmission distance. In the infrastructure based TDMA MAC, such as in cellular networks, the central controller proactively coordinates the nodes to avoid transmission collisions, where a node is scheduled to transmit in a time slot mainly when it has a packet to transmit. In contrast, in D-TDMA MAC due to the absence of a central controller, each node is required to exchange control signals for transmission scheduling and to determine the optimum number of time slots in a time frame, which is not efficient. To avoid spending a large amount of channel time in communication overhead, the number of time slots in each frame and the duration of each time slot are considered the system parameters and kept fixed in D-TDMA MAC. On the other hand, variations in vehicle density in the space and time result in under-utilization of the radio resources, in terms of unused time slots in a frame. The under-utilization occurs when there are not enough nodes in a two-hop neighborhood to use all the time slots of a frame. Moreover, D-TDMA MAC does not have any makeup strategy to handle a transmission failure resulting from the wireless channel impairments in VANETs. As frequent link breakage due to the dynamic networking conditions is common in VANETs, the lack of a makeup strategy in D-TDMA poses technical challenges in satisfying the strict QoS requirements. Hence, D-TDMA MAC is not always capable to support the wide range of mobile distributed applications, specifically when the channel is in a poor condition, and results in the wastage of time slots. Furthermore, it may not always be reliable to support delay sensitive messages for high priority safety applications. Though node cooperation can be used to alleviate such problems through cooperative relay transmissions and/or makeup transmissions, the existing works in link-layer cooperation cannot be applied directly in VANETs. Hence, VANETs require new solutions in its MAC layer as well as in cooperative communication to address the associated issues. A cooperation scheme in the MAC layer should be designed to support the wide range of applications and must provide efficient and reliable communication with fast broadcast service to satisfy strict QoS requirements.

In this book, we focus on developing a node cooperation framework, as one possible way to overcome the existing challenges, in the link-layer for reliable communication in VANETs. The framework is expected to enable cooperation among nodes when an ongoing transmission fails, and prevent possible packet dropping. In addition, the proposed framework can help to facilitate safety related applications to quickly broadcast the corresponding packets in an area of interest. In developing such a node cooperation framework, this book has the following research contributions:

- A node cooperation framework is developed for point-to-point communication in D-TDMA based MAC protocols for VANETs, which enables an efficient utilization of the available radio resources, improves the network throughput, and enhances the transmission reliability [1, 2];
- In the presence of high relative node mobility and channel fading, the effects of dynamic networking condition on the node cooperation framework are studied and a collision avoidance scheme is proposed to utilize cooperation opportunities efficiently without disrupting the normal operations of VANETs [3, 4];
- A node cooperation based makeup transmission framework is developed to guarantee fast dissemination of high priority safety messages to the maximum number of vehicles in an area of interest, without compromising the reliability and latency requirements [5].

1.4 Outline

The rest of this book is organized as follows. In Chap. 2, the state-of-art of MAC protocols for VANETs as well as link-layer node cooperation schemes are discussed. Chapter 3 describes the system model under consideration and associated assumptions. In Chap. 4, we present a novel cooperative MAC (CAH-MAC) protocol customized for D-TDMA MAC in VANETs. Performance evaluation of CAH-MAC is conducted to investigate its efficiency and reliability and to compare it with existing approaches [1, 2]. Chapter 5 discusses how node cooperation affects the operations of D-TDMA MAC. Enhanced CAH-MAC (eCAH-MAC), with collision avoidance scheme and other additional features, is proposed to tackle the negative effects of node cooperation on the normal operations of D-TDMA MAC protocols. Through extensive simulations and mathematical analysis, performance evaluation of eCAH-MAC is conducted to compare it with existing approaches [3, 4]. Chapter 6 presents the node cooperation for broadcast service in D-TDMA MAC. A node cooperation based makeup strategy is proposed with several helper selection schemes. The ability of the proposed framework to support safety applications in VANETs is investigated with optimization problem formulation and simulations [5]. Finally, Chap. 7 concludes this book and outlines some research topics for further investigation.

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Chapter 2
Background and Literature Review

This chapter provides the background information of VANETs that is related to our research. In reviewing recent literature, approaches proposed for the medium access control (MAC) in single-channel VANETs are presented. In addition, cooperative MAC protocols and cooperation based makeup transmission frameworks proposed in the literature in order to improve performance of wireless networks are discussed.

2.1 Medium Access Control in VANETs

Several approaches have been considered for designing a MAC protocol of VANETs. They are based on channel access schemes such as code division multiple access (CDMA), space division multiple access (SDMA), IEEE 802.11 random access, and time division multiple access (TDMA). MAC protocols based on CDMA channel access [1, 2] require each vehicle to have a database of allowable location-specific pseudo-random noise (PN) codes specified in its digital map. In addition, vehicles must be equipped with a large number of match filters, which depends on the length of PN codes. Similarly, MAC protocols based on SDMA channel access [3, 4] require each vehicle to have a location specific channel-allocation database in its digital map. These factors add complexity in the protocol development and make protocols difficult to implement. Hence, in the following, we focus only on MAC protocols based on IEEE 802.11 and TDMA channel access schemes, which are widely used in research studies related to VANETs.

2.1.1 IEEE 802.11

The IEEE 802.11 random access scheme is a well known MAC protocol in wireless networks [5]. Such a scheme allows a node to contend for the channel and access

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it if it is found idle. Variations in the IEEE 802.11 standard are made to make it suitable for a high mobility scenario, which is highly likely in VANETs. The IEEE 802.11p standard [6] is developed for VANETs, which targets to support vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. MAC protocols based on the IEEE 802.11p standard also support QoS provision and is governed by the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) standard [7], such that traffic packets are differentiated into four different access categories, $AC0$–$AC3$, where $AC0$ has the lowest priority and $AC3$ has the highest priority to access the channel. Service differentiation is achieved in terms of a back-off interval while accessing channel, such that a high priority traffic packet, in general, experiences a shorter back-off interval than that of a low priority packet. In [8], mathematical model to analyze the performance of IEEE 802.11p standard in terms of throughput is presented for a large scale vehicular networks providing in-vehicle Internet service. Although the IEEE 802.11 access scheme is considered in several studies to develop MAC protocols for VANETs, it suffers from the following problems.

- **Unbounded Latency**: IEEE 802.11 based MAC protocols suffer from an unbounded packet delivery latency in a high load condition [9]. In such a case, due to random access of the channel, a node may need to wait for a long duration or fail to access the channel [10] due to contentions and/or collisions.
- **Orphan Frame**: Feedback provisions such as acknowledgement (ACK) or clear-to-send (CTS) packets are used in IEEE 802.11 based MAC [11] to identify the transmission failure in point-to-point communication. In the IEEE 802.11 standard and its derivatives, a node attempts to retransmit a packet, for each failed transmission. It stops retransmission attempts either when it receives ACK from the target receiver or when the maximum retransmission limit is reached. This results in the orphan frame problem such that a source node, which failed to receive ACK, attempts to retransmit the packet which reached the target receiver. This phenomena can be common in VANETs with high relative mobility among nodes.
- **Broadcast Storm**: A broadcast storm occurs due to the random access of the channel [12, 13], when neighboring nodes attempt to flood a packet at the same time. Two or more neighboring nodes attempting to reserve the channel at the same time can result in transmission collisions and throughput reduction. A network layer (or routing) protocol can choose a relay node to rebroadcast a packet to alleviate such a phenomena in the IEEE 802.11 based networks [14].
- **Unreliable Broadcast Service**: In the IEEE 802.11p MAC protocol, even successful broadcast or multicast packets are left unacknowledged. This results in an unreliable broadcast/multicast service. Since broadcast service is critical to support safety related applications, MAC protocols based on the IEEE 802.11p standard may not be suitable for VANETs.

In addition, the performance of IEEE 802.11p MAC protocols gets adversely affected by the relative node mobility, which is a common phenomenon in VANETs [15]. On the other hand, the high priority safety messages in VANETs are short range, uncoordinated, and broadcast in nature [16]. They have a strict delay requirement and demand a reliable broadcast service. However, due to the aforementioned limitations, MAC protocols based on the IEEE 802.11 are not suitable to provide the required QoS in VANETs.

2.1.2 Time Division Multiple Access

In [12], the ADHOC MAC, a *distributed time division multiple access* (TDMA) based MAC protocol, abbreviated as *D-TDMA* MAC, is proposed for VANETs. The ADHOC MAC is based on RR-ALOHA [17] and supports reliable multihops, point-to-point, and broadcast services. The channel time is partitioned into time frames and each frame is further divided into a fixed number of time slots. Nodes contend for time slots. A single time slot is used by only one node within a two-hop transmission distance. Since each node, within its two-hop transmission distance, uses an unique time slot, the hidden node terminal problem is solved. In addition, the broadcast storm problem is solved as a node rebroadcasts a packet only when needed, i.e., if it does not sense retransmission of the packet from any of its neighboring nodes in the previous time slots. In [18], it is shown that the network throughput reduces due to the mobility among nodes in ADHOC MAC. Under such a mobile scenario, transmission collisions increase among vehicles moving in opposite directions or between vehicles and the stationary road side units (RSUs), reducing the throughput. VeMAC, an improved D-TDMA MAC, is proposed in [19] to minimize the throughput reduction due to the relative mobility as well as to provide a reliable broadcast service. Moreover, VeMAC has been implemented as a stand-alone protocol and tested with various experiments, demonstrating its potential to support road safety applications [20]. Thus, D-TDMA MAC protocols posses high transmission reliability as the probability of transmission collisions is low and they have explicit ACKs for each transmitted messages, as compared with the IEEE 802.11p [21]. However, dynamic networking conditions in VANETs result in the wastage of time slots in the D-TDMA MAC protocols. The wastage occurs when the number of nodes sharing a time frame is not enough to use all the available time slots of the time frame. Furthermore, upon a transmission failure, a source node has to wait until the next frame for retransmission despite the presence of unreserved time slots, during which the channel remains idle.

2.2 Link-Layer Cooperation

This section describes the cooperation objectives and issues at the MAC layer. In addition, cooperative MAC protocols proposed in the literature to mitigate the various wireless channel impairments are discussed.

2.2.1 Objective and Issues

In cooperative communications, a pair of source and destination nodes (an $s - d$ pair), with a poor channel condition, use the antenna of their common neighboring node(s), a helper node(s), to achieve transmission diversity. The helper node should have a better channel condition to both source and destination nodes. Cooperative relay transmission at the MAC layer can provide following advantages [22–26]:

- increasing the communication reliability even in a poor channel condition between $s - d$ nodes,
- increasing the throughput of an individual link as well as of the overall network,
- reducing the transmission power, thus reducing interference and improving spatial frequency reuse,
- reducing the energy consumption in an energy-constrained wireless network, and
- increasing the transmission range of a node and consequently the coverage area of the network.

Implementation of cooperation can be beneficial and can improve the performance of the MAC protocol. However, to exploit the benefits of the cooperation, the following fundamental decisions must be appropriately made [23, 27]:

- *When to Cooperate*: When a helper should offer to cooperate is the first key decision. For example, the helper may offer cooperation after it receives signalling messages such as request-to-send (RTS) and clear-to-send (CTS) , if it can increase the data rate between the $s - d$ pair or a source/destination may ask for help from its neighboring node(s) before establishing connection (transmitting RTS and/or CTS packets) to improve the transmission data rate. Based on the cooperation decision, cooperative MAC (cooperation enabled MAC layer protocol) is classified as either a proactive or a reactive cooperative MAC protocol. In a proactive protocol, the $s - d$ pair requests for cooperation proactively from a helper before a packet transmission. In contrast, in a reactive protocol, cooperation is trigged only after a communication failure between the $s - d$ pair.
- *Who are the potential helpers*: How does a node decide if it can be a helper and provide cooperation to an ongoing transmission between an $s - d$ pair? One of the primary metrics for this decision is the effective transmission rate between the $s - d$ pair with cooperation enabled transmission. Cooperation is performed if the transmission rate with cooperative relay transmission through the helper is higher than that of direct transmission between the $s - d$ pair.
- *How to support concurrent transmissions*: The introduction of the helper-destination transmission increases the interference range, such that nodes in the neighborhood of a helper are affected in addition to the neighboring nodes of the $s - d$ pair. Hence, cooperative relay transmission between the helper and destination must not interfere any ongoing transmission in the helper's neighborhood.

Moreover, signalling overhead due to the introduction of cooperation must not be significantly high as compared with payload data, otherwise cooperation may reduce throughput and may not be beneficial [28].

2.2.2 Link-Layer Cooperation

To exploit the benefits of node cooperation, several cooperative MAC protocols have been proposed for the legacy IEEE 802.11 networks with distributed control [23, 24, 29–33]. In [29] and [30], the cooperative MAC schemes (namely rDCF and CoopMAC respectively) exploit the multi-rate capabilities of the IEEE 802.11 networks. Helper nodes are chosen to shorten the transmission time of a packet. In [31], a similar cooperation scheme called CC-MAC is proposed for uplink transmission. The CC-MAC reduces occurrences of a transmission bottleneck due to congestion in the vicinity of access points and allows the nodes to perform concurrent transmissions which further increase throughput. In all aforementioned studies, cooperation is performed based on previous transmission attempts. In [23], it is shown that cooperation based on historical transmissions does not work for a network where nodes are moving with high relative mobility. Changes in traffic load, channel condition, network topology are frequent and common in MANETs, hence historical transmissions may not correctly reflect the present channel condition. In such a case, it is very likely that the source does not find helpers, or helpers fail to perform cooperation. This results in a delay in packet delivery and/or a throughput reduction.

Motivated by issues with cooperation based on historical transmissions, authors in [24, 32, 33] propose cooperative MAC protocols in which decision of cooperation and helper selection are made during the ongoing transmission. Cooperation decisions are made based on the strength of control signal and/or information exchange among nodes. In [32], the CD-MAC is proposed to improve transmission reliability in which the source node searches for a helper to retransmit its packets, if the destination sends the negative acknowledgement or does not acknowledge the reception. Similarly in [33], cooperation is enabled when vehicles missed broadcast packets from an RSU, such that helper nodes are selected to rebroadcast the packets, improving the overall throughput of a network and avoiding collision due to rebroadcasting. In [24], Zhou et al. propose a cooperative MAC protocol, ADC-MAC, which is backward compatible with the IEEE 802.11.

All of the aforementioned cooperative MAC protocols are based on the IEEE 802.11 and force neighboring nodes to stop their transmissions during the cooperative transmission for an $s - d$ pair. Nodes in the vicinity of the helper along with the $s - d$ pair should back-off their transmissions until the ongoing transmission finishes. In addition, the interference area increases with the introduction of helpers, which further increases the probability of hidden and exposed node problems. Node cooperation mechanisms for TDMA MAC are presented for infrastructure based wireless networks in [34–36]. As communication links are established between a central controller (or access point) and mobile nodes in such networks, cooperative relay transmission is performed by dedicated helper nodes and coordinated by the controller. Furthermore, there are dedicated time slots to perform cooperation which are allocated to helper nodes even if cooperation is not required. Thus, such schemes cannot be applied directly in VANETs. When VANETs use D-TDMA, operations must be performed in distributed manners, which involve cluster formation, slot allocation and cooperation decisions. Focusing on distributed operations, in [37–39], node cooperation schemes with distributed cooperation decisions are presented. In [37], a node cooperation scheme is presented in which helper nodes perform dynamic cooperative retransmission to the target receiver during the source node's time slot. However, application of such cooperative retransmission to VANETs is not straightforward as each node with a time slot must broadcast its neighborhood information to its nearby nodes in every frame, in order to continue using its time slot in the next frame. In [38, 39], node cooperation schemes are presented for multi-hop communication by using idle time slots. Such schemes require acknowledgement (ACK) from the target relay node, during the source node's time slot. Neighboring nodes participate to perform cooperative relay transmission only if they have the packet and do not receive ACK from the target relay node. However, such a scheme leads to a large (and may be variable) time slot duration in order to accommodate ACKs during the source node's time slot, which is not desirable. Hence the aforementioned node cooperation schemes cannot be directly applied in VANETs.

2.2.3 Cooperation for Makeup Transmission

A makeup strategy is a proactive process in which transmission failures, that might have happened when a source node broadcasts a packet, are corrected before the detection of such transmission failures by the source node [40]. Several makeup strategies have been proposed to improve the reliability, latency and efficiency of broadcast service in wireless networks. When an opportunistic makeup strategy is deployed [40], neighboring nodes of a source node (that received the packets from the source node) rebroadcast the packets with probability 1, until the predefined QoS is achieved. In a probabilistic scheme, packets are rebroadcast with a predetermined probability [41]. Such a decision to rebroadcast the packet does not address the effects of dynamic networking conditions, which may lead to wastage of makeup opportunities when relay nodes are not in a good channel condition to the nodes that failed to receive the packet from the source node. Different form these schemes, in [40, 42–44], the probability of rebroadcast is calculated based on the distance or position of the source node with respect to the node that performs rebroadcast. Such position based makeup strategies are suitable for relaying a packet in a multi-hop scenario, so that packets can be delivered to the nodes beyond one-hop transmission distance from the source node. Similarly, in [14], a received signal strength (RSS) based makeup strategy uses instantaneous channel condition information to perform makeup transmissions. Such a scheme requires additional transmission overhead in terms of signalling and time to choose the best relay node. This results in a longer, and may be variable, time slot duration to accommodate the signalling and relay selection, which is not desirable in D-TDMA MAC. Thus, the existing makeup strategies either do not address the dynamic networking scenario in VANETs or are not suitable for D-TDMA MAC based broadcast services. Moreover, the node cardinality of a relay node must be considered to ensure that a maximum number of nodes, which fail to receive the packet from a source node, will receive the packet before it expires.

2.3 Summary

In this chapter, existing MAC protocols proposed for VANETs and their limitations are discussed. The IEEE 802.11p and distributed TDMA based MAC approaches are not free from packet dropping and throughput reduction due to a poor channel condition. Further, these approaches can be inefficient in utilizing the available radio resources. On the other hand, CDMA and SDMA based MAC protocols are not realistic to implement in VANETs. Such limitations can be resolved by introducing cooperation among nodes in the MAC layer. Existing studies in link-layer cooperation focus on cooperation in the IEEE 802.11 based networks and/or infrastructure based TDMA network, which cannot be directly implemented in VANETs. Moreover, VANETs require more from the cooperation at the MAC layer to enhance the reliability of the broadcast service. In this book, we focus on the operations in a control channel MAC protocols in VANETs. Thus, this chapter focuses on the VANETs that operate in a single frequency channel. Multi-channel operations in VANETs, including multi-channel MAC protocols and node cooperation in multi-channel environments, are discussed in Appendix A.

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Chapter 3
System Model

This chapter describes the system model under consideration and necessary assumptions made regarding network topology, communication among nodes, channel access, and node distribution.

3.1 Network Topology and Communication Among Nodes

Consider a VANET consisting of vehicles moving with the same average speed and distributed randomly along a one-way multi-lane road segment. The road segment consists of L lanes, each with width w_l, $l \in \{1, 2, 3, \ldots, L\}$. Vehicles cannot communicate with each other beyond their transmission range, denoted by R in meters, taking account of a possible poor channel condition. Each node transmits a packet with constant transmission power, denoted as P_t. The instantaneous received power at a receiving node which is at r meters from a transmitting node is denoted by γ_r. To successfully receive a packet from a transmitting node, the instantaneous received power γ_r must be equal to or greater than a threshold value, denoted as γ_{th}. All vehicles are identical, in a sense that they have the same R, P_t and γ_{th} values.

3.2 Channel Access

We focus on the operations in a control channel of VANETs. In VANETs, the control channel is used to exchange safety messages and other control information among one-hop neighbors and for negotiation between a pair of service provider and user to access the service channels (see Appendix for the detail of multi-channel operations in VANETs). The channel access mechanism is based on D-TDMA MAC protocols, such as ADHOC MAC and VeMAC, such that the channel time is divided into

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frames and each frame consist of a constant number of time slots, denoted by F. Each time slot has a constant time interval. Each vehicle knows the number of time slots per frame and is capable of detecting the start time of a frame and, consequently, the start time of a time slot.

3.3 Time Synchronization Among Vehicles

Partitioning the channel time into the fixed number of time slots and accessing a time slot once in a frame demand precise time synchronization among nodes. Here, each vehicle is equipped with a Global Positioning System (GPS) receiver that receives the one-pulse-per-second (1PPS) signal every second [1, 2]. When the number of frames per second is an integer, denoted by T (in frame per second), the rising edge of each 1PPS signal can be taken as the reference instance of the start of a frame as illustrated in Fig. 3.1. Thus, with the knowledge of the number of time slots per frame, the number of frames per second, and the duration of a time slot, each vehicle can detect the start time of a frame.

A GPS receiver's local oscillator can be used for time synchronization when the GPS signal is lost for a short duration [3]. On the other hand, upon loosing the GPS signal for a longer duration, various distributed synchronization schemes can be used for time synchronization [3].

3.4 Neighboring Nodes

In order to access the channel without any conflicts, each node maintains sets of its one-hop and two-hop neighbors, refereed to as one-hop set (OHS) and two-hop set (THS) respectively. Nodes in OHS and THS are those which can be reached at maximum one and two hops of transmission respectively from a reference node. Consequently, a reference node can communicate with all of its one-hop neighbors, OHS nodes. Figure 3.2 illustrates one-hop and two-hop sets with node A as a reference. The reference node, A, is a member of two OHSs namely OHS 1 and OHS 2 and a THS namely THS 1.

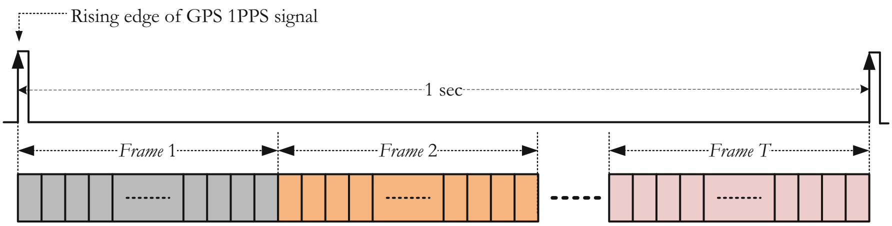

Fig. 3.1 Use of the 1PPS signal for time synchronization

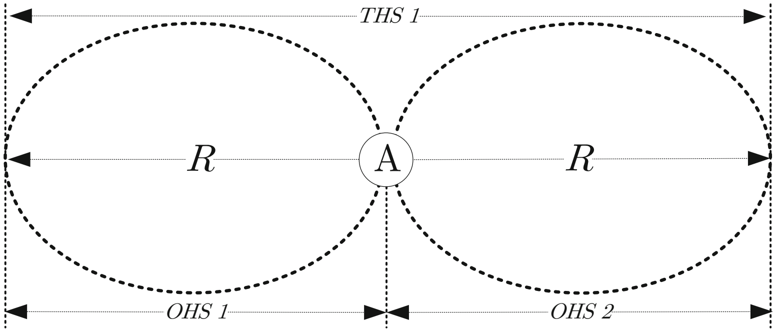

Fig. 3.2 A two-hop set of reference node A, where an *ellipse* represents an OHS, within which nodes can directly communicate with each other [4]

THS nodes form a cluster to share a time frame and to access a time slot. Such a cluster is the group of nodes which are at a maximum two-hop transmission distance from each other. For the operations of D-TDMA, a cluster head is not required and a node can be a member of multiple clusters. Such clusters are mainly formed in a network to stop simultaneous usage of a time slot by more than one node within the two-hop transmission distance and to avoid the hidden node problem in D-TDMA.

3.5 Reservation and Retention of Time Slots

To access the channel, a node must acquire a time slot. In each time frame, a node accesses the channel only in its own time slot if it already has a reserved time slot, or otherwise selects a time slot for slot acquisition based on information about its THS nodes and the corresponding time slot ownership. A node, without a time slot, contends to reserve a time slot with other similar nodes in its THS. To do so, it first listens to the channel over a period of F consecutive time slots (not necessarily in the same frame), then selects one time slot among the unreserved ones, if available, and finally, reserves the selected unreserved time slot. In a case where multiple nodes in each others' THS attempt to reserve the same time slot, an access collision occurs at their common OHS nodes. A node, after suffering from an *access collision*, repeats the aforementioned time slot reservation process. Upon a successful time slot reservation, a node transmits a packet in its own time slot in every frame until it suffers from transmission failure or transmission collision. While accessing their own time slots, nodes can suffer from *merging collision* due to relative mobility [5]. When nodes of the same time slot but belonging to different THSs move into each others' two-hop transmission range, a transmission collision occurs in the form of merging collision at their common one-hop neighbors [6]. Due to merging collisions, D-TMDA MAC, such as ADHOC MAC, suffers from throughput reduction [6]. To minimize merging collisions and throughput reduction, time slots can be separated into three disjoint groups as in VeMAC [7]. Such disjoint groups of time slots are dedicated to vehicles moving in opposite directions and to RSUs respectively, which reduces the probability of merging collisions due to relative node mobility and overcome throughput reduction.

This book focuses on node cooperation at the link-layer of VANETs. In order to study such cooperation mechanisms to improve system throughput and transmission reliability, a VANET consisting of nodes perfectly synchronized in time is considered. Furthermore, D-TDMA operations such as for reserving a time slot, packet transmission, detection of transmission failures and transmission collisions are done in a distributed manner as in [7, 8].

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Chapter 4
Cooperation in ADHOC MAC

This chapter presents a node cooperation scheme, referred to as *Cooperative ADHOC MAC*[1] (CAH-MAC), mainly focusing on the MAC layer in VANETs [1, 2]. As discussed in Sect. 2.2.2, existing works on link-layer cooperation are not suitable for VANETs scenarios and cannot be applied directly. Different from the existing works, here we consider a VANET using a distributed TDMA based MAC. In the system, nodes reserve their time slots and nearby nodes form a cluster to share a time frame. For cooperation at the link layer, a helper node utilizes an idle time slot to relay a packet that a source node failed to deliver to the target destination node in a direct transmission due to a poor channel condition. Furthermore, cooperative relay transmissions in the proposed node cooperation scheme do not affect the normal (non-cooperation) transmissions. Using idle time slots for the cooperative relay transmissions, the proposed CAH-MAC protocol improves system throughput and transmission reliability of the D-TDMA MAC for VANETs.

With a focus on cooperation to improve transmission efficiency, we consider a network where nodes have already reserved their time slots and have information to transmit in each frame targeting specific destination nodes. Thus, nodes access the channel once in every frame in their respective time slots. Access collisions do not occur, and cooperation is performed by only those nodes which have their own time slots to access the channel. Furthermore, nodes move with negligible relative mobility over an observation period (duration of a time frame). Hence, they are stationary with respect to each other, maintaining a fixed network topology during the observation period. As the relative mobility among nodes is negligible, merging collisions do not occur. Thus with no merging and access collisions, a reserved time slot is always dedicated to its owner.

To investigate the effects of channel quality, we consider that the nodes within the transmission range of a source node can successfully receive the transmitted packets

[1]The name Cooperative ADHOC MAC is given as node cooperation is performed over the distributed TDMA MAC, namely ADHOC MAC.

S. Bharati, W. Zhuang, *Link-Layer Cooperative Communication in Vehicular Networks*, Wireless Networks, DOI 10.1007/978-3-319-58721-9_4

with probability p. Thus, the parameter, p, represents the channel characteristics. The larger the p value, the better the channel quality. However, the parameter, p, does not account for transmission failures due to transmission collisions when multiple nodes within each other's interference range transmit during the same time slot. As transmission collisions do not occur in the system under consideration, the p value represents the probability of no transmission errors between a pair of nodes.

We derive a close-form expression for the throughput and packet dropping rate of the newly proposed CAH-MAC protocol, which is verified using simulations. Our analysis shows that the CAH-MAC protocol achieves a higher throughput and a lower packet dropping rate than that of the ADHOC MAC under a similar networking condition. Numerical results demonstrate that the performance gain due to node cooperation is significant when the channel is in a moderate condition (i.e., moderate p value). In addition, the gain is significant in the presence of a moderate number of nodes in a two-hop neighborhood relative to the number of time slots available in a frame.

4.1 CAH-MAC Basics

In this section, we discuss the detail operation and different components of CAH-MAC, including packet structure, cooperation decisions, and helper selection. A node accesses the channel once in every frame in its own time slot. During the time slot, the node transmits a packet that consists of frame information (FI), cooperation header (COH), packet header (PH), payload data, and cyclic redundancy check (CRC), as illustrated in Fig. 4.1. The structure and objectives of PH, payload data, and CRC are similar to those in ADHOC MAC and VeMAC, whereas the formant of FI is different in CAH-MAC. In addition, CAH-MAC uses a new field, namely COH, specifically to perform node cooperation. In the following, we describe the structure and purposes of FI and COH.

4.1.1 Frame Information

The fame information (FI) is a collection of identifier fields (IDFs) as shown in Fig. 4.2. The number of IDFs in an FI is equal to F, the number of time slots per frame. Each IDF is dedicated to the corresponding time slot of a frame, i.e., the index

Frame Information (FI)	Cooperation Header (COH)	Packet Header (PH)	Payload Data	CRC

Fig. 4.1 Packet structure in CAH-MAC [2]

IDF-1	IDF-2	IDF-3	---	IDF-(F-1)	IDF-F
id_a	ϕ	id_b	---	ϕ	id_z

Fig. 4.2 Structure of a frame information field, where ϕ indicates an empty field [2]

of the IDF field in FI represents a time slot with the same index in the corresponding time frame. Temporary (and short) identifier, whose size is shorter ($\simeq$1–2 bytes) than the size of a MAC address, is used as an ID of a node [3, 4]. Such a short ID is selected randomly by a node and changed if there is a conflict [3]. The use of such short IDs reduces the size of an FI, which ultimately reduces the MAC overhead in the proposed protocol.

A node, say D, upon receiving a packet successfully in the sth time slot from a source node, say S, concludes that the sth time slot belongs to node S. Node D then puts the ID of node S in the sth IDF of its FI. Furthermore, upon successfully receiving a packet from node S in the sth time slot, node D knows

1. the existence of node S as its one-hop neighbor,
2. node S is the owner of the sth time slot, and finally
3. information that is embedded in node S's FI, i.e., IDs of one-hop neighbors of node S and indices of their corresponding time slots.

Furthermore, the FI can be used to detect transmission status and for transmission acknowledgement in D-TDMA. For example, consider that node D fails to receive the packet that node S transmitted in the sth time slot. In such an event, node D does not include the ID of node S in IDF-s of its FI, as IDF-2 and IDF-($F-1$) in Fig. 4.2. Upon receiving the FI from node D, node S concludes a transmission failure between itself and node D in the sth time slot, which is basically a negative acknowledgement (NACK). Similarly, inclusion of the node S's ID in the FI of node D serves as the acknowledgement (ACK) of a successful transmission from node S to node D. Moreover, if there is no signal or if a channel error or transmission collision occurs during a time slot, node D treats the time slot as an unreserved one. Hence, after listening the channel for F consecutive time slots and from all the FIs that it received successfully from its one-hop neighbors, a node determines:

1. the set of all of its one-hop neighbors, i.e., its OHS,
2. the set of all of its two-hop neighbors, i.e., its THS, and
3. the owner of each time slot in a frame, i.e., time slot ownership information of the corresponding frame.

Note that a node updates its neighborhood sets, i.e., OHS and THS, based on packets it received successfully from nodes in its one-hop neighborhood. These packets can be broadcast, unicast, or multicast packets. Furthermore, based on FIs it has received, a node can identify unreserved time slots which are not being used by any of its two-hop neighboring nodes. Thus, the FI facilitates in neighborhood discovery, formation of a THS cluster, selection of an undeserved time slot for time slot acquisition, and transmission acknowledgement.

4.1.2 Node Cooperation Mechanism

Cooperative relay transmission is always performed by a one-hop neighbor of the source and destination nodes (the $s-d$ pair). It is highly likely that the channel condition between the $s-d$ pair remains the same during the unused time slot as that during the source node's time slot. Thus, retransmission by the source node during the unused time slot likely is not helpful and waste the transmission opportunity. In contrast, cooperative relay transmission of a packet, through an independent channel (i.e., from a helper node to the destination node) during an unreserved time slot, provides transmission diversity and hence improves transmission reliability even if the channel condition between the $s-d$ pair is poor [5]. In the following, we discuss how a node decides to cooperate for an $s-d$ pair that suffers from a poor channel condition.

Let $\mathcal{F} = \{1, 2, 3, \ldots, F\}$ denotes the set of time slots in a frame. Let $\mathcal{O}_x$ and $\mathcal{T}_x$ denote the OHS and THS of a node x. Let $\mathcal{B}_x$ denotes the set of all time slots which belongs to the THS nodes of node x, i.e., any time slot $t \in \mathcal{B}_x$ is reserved from the perspective of node x. Consider S and D as a pair of source and destination nodes, an $s-d$ pair, which own the sth and dth time slots of the frame respectively. Let a helper node be denoted as H. Cooperation decision and cooperative relay transmission are performed only if all the following conditions are satisfied [2]:

1. **The direct transmission fails**: A node performs cooperation when the direct transmission between the $s-d$ pair fails. Upon a transmission failure, node D does not acknowledge the transmission from node S, such that $S \notin \mathcal{O}_D$.
2. **The helper successfully receives a packet for retransmission**: A node can offer cooperation only if it receives the packet successfully from the source node S during the sth time slot.
3. **The destination is reachable**: Node H can relay the packet, if it is in the one-hop transmission distance from the destination node and detects the transmission failure from node S to node D after receiving the FI from node D. Hence, both $s-d$ nodes must be listed as one-hop neighbors in node H's OHS, i.e., $S, D \in \mathcal{O}_H$. Such nodes which can potentially perform cooperative relay transmission are referred to as potential helper nodes.
4. **There is an available time slot**: Potential helper node H, when conditions (1)–(3) are satisfied, can offer cooperation if there exists at least one unreserved time slot $h \in \mathcal{F}$ during which it can perform cooperative relay transmission. The transmission from H during the hth time slot shall not cause any collision at its two-hop neighbors, i.e. $\forall h \notin \mathcal{B}_H$.

If all the aforementioned conditions are satisfied, a potential helper nodes can offer cooperation to the $s-d$ pair. If there are multiple potential helper nodes, the one which first announces to help will relay the packet while all other potential helper nodes suspend their cooperation decision for the same packet. As the potential

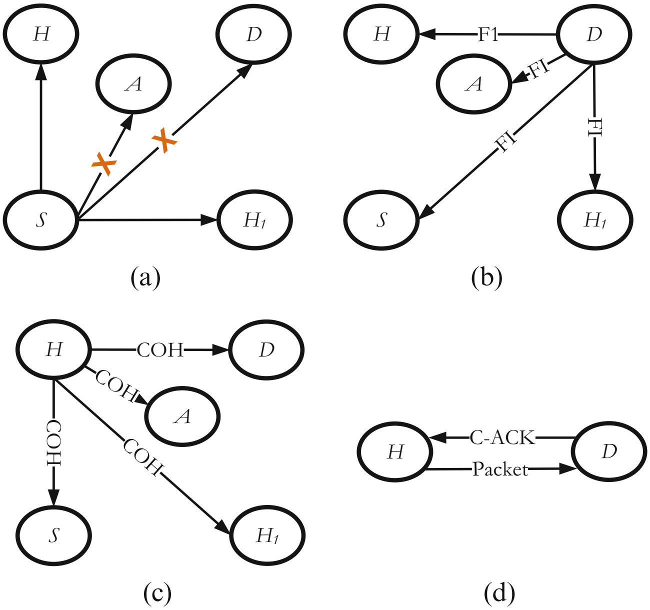

Fig. 4.3 Cooperation operations and information exchanges in the CAH-MAC [1, 2]: (**a**) Phase 1: Source node fails to transmit a packet to the destination; (**b**) Phase 2: Neighboring nodes detect transmission failure after examining the FI from the destination; (**c**) Phase 3: Helper node *H* offers cooperation; (**d**) Phase 4: Helper node *H* re-transmits the packet that failed to reach the destination after receiving a cooperation acknowledgement from the destination

helper nodes wait for their respective time slots to offer cooperation, for a given $s - d$ pair, the helper node among all the potential helper nodes is the one whose time slot is the earliest after the detection of transmission failure.

Figure 4.3 shows necessary information exchanges to perform cooperative relay transmission in the CAH-MAC. Cooperation may be performed only when target destination node D fails to receive a packet transmitted by source node S (in Fig. 4.3a). Upon failing to receive the packet, node D announces transmission failure through its FI as in Fig. 4.3b. Accordingly, nodes H and H_1 detect the transmission failure between the $s - d$ pair. Upon deciding to cooperate, node H scheduled cooperative relay transmission in the hth time slot and transmits its decision through cooperation header (COH) in its packet as in Fig. 4.3c. Note that as helper node H's time slot is earlier than that of potential helper node H_1, node H offers cooperation and node H_1 suspends its cooperation decision after receiving COH from node H. In hth time slot, node D transmits a cooperation acknowledgement (C-ACK) to avoid transmission collision during the selected unreserved time slot. After receiving the C-ACK from destination node D, helper node H relays the packet to node D (in Fig. 4.3d). Next, we discuss COH that a helper node uses to offer cooperation and C-ACK that a destination node transmits during an unreserved time slot.

4.1.3 Cooperation Header and Cooperation Acknowledgement

A potential helper node, after deciding to cooperate an $s - d$ pair, transmits its decision via COH in its packet. A node puts the following information in the COH:

1. its intention to cooperate,
2. the index of time slot of the source node during which transmission failure occurred, and
3. the index of the selected unreserved time slot in which the packet will be retransmitted from the helper to the destination.

The helper node puts the COH, with the aforementioned information, in its packet and transmits the packet during its time slot. As helper node is the one which first offers cooperation for the $s - d$ pair, other potential helper nodes, if exist, suspend their intentions after receiving the cooperation decision from the helper node. Suspension of cooperation intention from other potential helpers, that are in one-hop distance form the helper node, avoids transmission collision during cooperative relay transmission. However, collisions occur at the destination node when two or more potential helper nodes, which are not in each other's one-hop distance, offer cooperation at the same unreserved time slot. C-ACK is transmitted by the destination node during the selected unreserved time slot to avoid such transmission collisions, which is illustrated in Fig. 4.4. Destination node transmits C-ACK to accept cooperation, in which it includes the ID of the first potential helper which offered cooperation. After receiving C-ACK from the destination node, the selected helper node relay the packet that failed to reach the destination in the direct transmission from the source node. Other potential nodes, on the other hand, suspend their relay transmission when they do not detect their IDs in the C-ACK. Thus, the transmission of C-ACK from a destination node avoids any possible transmission collisions as it forces potential helpers to suspend their transmissions and only allows the selected helper node to perform cooperative relay transmission.

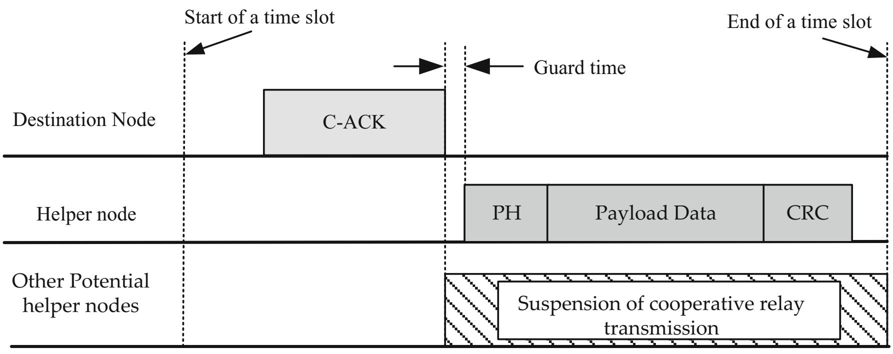

Fig. 4.4 Cooperative relay transmission during an unreserved time slot [2]

The number of short IDs is always enough to be shared among the nodes that are sharing a frame (at a time a maximum number of F nodes can share a frame). Hence, the size of an index of a time slot is comparable with the size of a short ID. Consequently, the size of COH is negligible as compared to the size of FI (and obviously the size a packet), which has a space for F IDs. Generally, the F value is set large enough to guarantee a time slot for each node. In addition, C-ACK and cooperative relay transmission are performed in an unreserved time slot, which would be wasted in the absence of node cooperation. Hence, cooperation can be performed at the cost of negligible overhead. Moreover, in the proposed CAH-MAC, only one helper performs the cooperative relay transmission for a failed $s-d$ direct transmission. Potential helpers, which can offer cooperation to the failed $s-d$ direct transmission, suspend their cooperation intentions once they receive cooperation decision from the helper node. Hence, a potential helper offers cooperation to only those failed $s-d$ direct transmissions which are not offered with cooperation, but not to every failed $s-d$ direct transmissions. This reduces the size of COH and hence the communication overhead due to cooperation.

4.2 Preliminaries for the Performance Analysis

In this section, we present preliminaries required for performance evaluation of the proposed CAH-MAC protocol. Parameters such as throughput and transmission reliability are considered to compare the performance of CAH-MAC with ADHOC MAC.

4.2.1 Node Distribution

Along a lane of the considered road segment, nodes are distributed randomly with an exponentially distributed inter-vehicular distance. It is to be noted that, such an assumption for inter-vehicular distance is valid when the roadways are not in their full capacity and vehicles have low interaction among each other in their movements, such that the inter-vehicle distances are independent and identically distributed (i.i.d.) with an exponential probability density function (pdf) [6]. Let ρ_l, $l \in \{1, 2, 3, \ldots, L\}$, denotes the vehicle density of lane l in terms of the number of vehicles per unit length. The number of vehicles over a given length of road-segment follows a Poisson process, such that the probability of finding n vehicles along a given length z of the road segment is given by

$$p(n,z) = \frac{(\rho z)^n e^{-\rho z}}{n!}, \qquad n = 0, 1, 2, \ldots \tag{4.1}$$

where $\rho = \sum_{l=1}^{L} \rho_l$.

For tractable analysis, (4.1) is approximated by considering vehicles as points in a line representing a roadway. In reality, as two adjacent vehicles in the same lane always maintain a minimum safety distance (MSD) to avoid any vehicle collision between them, the inter-vehicular distance follows a shifted negative exponential distribution [7].

4.2.2 Distribution of the Number of Neighboring Nodes

Let N_T denotes the number of nodes which are in each other's two-hop transmission distance and sharing a same frame. As illustrated in Fig. 3.2, nodes in a given THS are distributed within distance of R meters in either directions of a reference node (including itself). Thus, N_T includes all nodes along the road segment of length $2R$. As the counting of nodes follows a Poisson distribution, the probability mass function (pmf) of N_T can be obtained by substituting $z = 2R$ in (4.1), given by

$$\begin{aligned}\Pr\{N_T = n_t\} &= p(n_t, 2R) \\ &= \frac{(2\rho R)^{n_t} e^{-2\rho R}}{n_t!}, \qquad n_t = 0, 1, 2, \ldots .\end{aligned} \tag{4.2}$$

A node cannot access time slots that are being used by nodes in its THS. Thus for stable performance of D-TDMA MAC, F must be large enough so that each node in a THS, i.e., nodes distributed along the road segment of $2R$ meters, gets a unique time slot. Hence, we should have $F > \overline{N}_T = 2\rho R$ to achieve stable performance of the MAC protocol.

Let N_o denotes the number of nodes which are in OHS of both source and destination nodes, referred to as common OHS nodes of the $s-d$ pair. Figure 4.5 illustrates the road segment where such nodes are distributed. In Fig. 4.5, nodes which are in OHS of both source and destination nodes are distributed along the road segment of length $2R-r$ meters, where r ($\leq R$) is the distance between the $s-d$ nodes. If r is uniformly distributed within $[0, R]$, the average distance between the $s-d$ nodes $0.5R$. Consequently, common OHS nodes are distributed along length of $1.5R$ meters on average. Hence, the pmf of N_o can be obtained by substituting $z = 1.5R$ in (4.1), given by

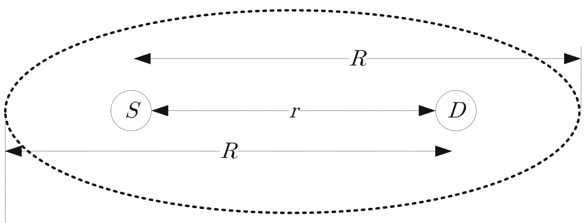

Fig. 4.5 Illustration of the common coverage road segment of an $s-d$ pair [2]

$$\begin{aligned}\Pr\{N_o = n_o\} &= p(n_o, 1.5R) \\ &= \frac{(1.5\rho R)^{n_o} e^{-1.5\rho R}}{n_o!}, \quad n_o = 0, 1, 2, \ldots .\end{aligned} \tag{4.3}$$

4.2.3 Transmission During a Time Slot

A node performs direct transmission during its own time slot, i.e., during a reserved time slot, or cooperative relay transmission during an unreserved time slot. Within the transmission range R, the channel is characterized by p such that the probability of the channel being in a good condition during a given time slot is given by

$$\Pr\{\gamma_r \geq \gamma_{th}\} = \begin{cases} p, & \text{if } 0 < r \leq R \\ 0, & \text{otherwise} \end{cases} \tag{4.4}$$

where r is the distance between the $s-d$ pair. Let p_s and p_c denote the probabilities of successful packet transmission and transmission collisions respectively during a given time slot. As discussed in Sect. 3.5, merging collisions are due to the relative mobility among nodes and access collisions in the process of time slot reservations. In the system under consideration, as nodes are relatively stationary with respect to each other and have already reserved their time slots, there are no transmission collisions. Hence $p_c = 0$. As channel condition and transmission collision are independent of each other, p_s is given by

$$\begin{aligned}p_s &= (1 - p_c)p \\ &= p.\end{aligned} \tag{4.5}$$

In the following, we use p_s to derive necessary distribution functions required for the performance analysis of the CAH-MAC.

4.2.4 Types of Time Slots and Their Distributions

In a given frame, out of the total F time slots, each time slot is one of the following three types:

1. ***Unreserved***: Time slots which are not owned by any nodes in the two-hop neighborhood are unreserved time slots. On the other hand, reserved time sots are any time slots other than unreserved ones in a frame which are owned by the corresponding THS nodes. Let random variable U denote the number of unreserved time slots in a frame.

2. ***Successful***: The reserved time slots during which their owner nodes successfully deliver packets to the target destination nodes are regarded as successful time slots. Let random variable X denote the number of successful time slots in a frame. Hence, given $U = u$, the number of reserved time slots is $F - u$ and we have $0 \leq X \leq F - u$.
3. ***Failed***: The reserved time slots other than successful ones in a frame are regarded as failed time slots.

Note that when node cooperation is enabled, for each failed direct transmission, an unreserved time slot is used for the cooperative relay transmission if conditions given in Sect. 4.1.2 are satisfied. With node cooperation, an unreserved time slot selected for cooperative relay transmission is considered a successful time slot if a packet is successfully delivered to the target destination through the helper node, and a failed time slot otherwise.

The number of reserved time slot in a frame is bounded by the number of corresponding THS nodes. In a frame with total F time slots, no more than N_T time slots are reserved by members of the corresponding THS. On the other hand, unreserved time slots are leftover time slots after all members of the THS finished their reservations. Hence we have

$$U = \begin{cases} 0, & \text{if } N_T \geq F \\ F - N_T, & \text{if } 1 \leq N_T < F. \end{cases} \tag{4.6}$$

Note that in (4.6), for a time slot to be called as reserved (or unreserved) or for a frame to exist, there must be at least one node in the corresponding THS, i.e., $N_T \geq 1$. Hence, if a frame exists, we have $0 \leq U \leq F - 1$. On the other hand, if there are more than F nodes in a THS, there will be no unreserved time slot in the corresponding frame, i.e., $U = 0$. Hence, from (4.2) and (4.6), the pmf of U is given by

$$\Pr\{U = u\} = \begin{cases} 1 - \sum_{i=1}^{F-1} \frac{(2\rho R)^i e^{-2\rho R}}{i!}, & \text{for } u = 0 \\ \frac{(2\rho R)^{F-u} e^{-2\rho R}}{(F-u)!}, & \text{for } 0 < u \leq F - 1. \end{cases} \tag{4.7}$$

4.2.5 Cooperation Enabled Transmission

Cooperation is triggered for a transmission failure only if the conditions in Sect. 4.1.2 are satisfied. Based on the operation procedure discussed in Sect. 4.1, such conditions can be represented by the following two events:

- *Event 1* (E_1): There is at least one potential helper node which are in the same OHS of the $s - d$ nodes. In addition, potential helper nodes successfully received the packet, during the source nodes's time slot, that failed to reach the destination.

- *Event 2* (E_2): There exists at least one unreserved time slot in which a potential helper node can transmit without causing any collision(s) in its OHS neighborhood.

An occurrence of event E_1 depends on the channel conditions between the source node and common one-hop neighbors of the $s-d$ pair. On the other hand, from (4.6) and (4.7), an occurrence of event E_2 depends on the number of THS members and F value. Hence, events E_1 and E_2 are independent of each other. Cooperation is triggered if both events E_1 and E_2 occur. Thus, the probability of cooperation decision for each failed direct transmission, denoted as p_{coop}, is given by

$$p_{coop} = \Pr\{E_1\}\Pr\{E_2\}. \tag{4.8}$$

In the following, we derive close-form expressions of the probability of occurrence of events E_1 and E_2 respectively.

4.2.5.1 Existence of Potential Helpers (Event 1)

Common OHS neighbors of an $s - d$ pair, which receive a packet from the source node, are potential helper nodes of the $s - d$ pair. The number of such potential helper nodes for a given failed direct transmission between an $s - d$ pair follows a binomial distribution. Let random variable Y denotes the number of potential helper nodes. Given $N_o = n_o$, potential helper does not exist if $n_o \leq 2$, as $s-d$ pair cannot be their own helper node. If $3 \leq n_o \leq F$, up to $n_o - 2$ nodes can act as helper nodes if they successfully receive the packet from the source node. Finally if $n_o > F$, only $F-2$ which own a time slot in a frame can act as helper nodes. A node, which does not own a time slot cannot transmit its COH, hence it cannot perform cooperation. Therefore, given $N_o = n_o$, the pmf of Y is given by

$$\Pr\{Y = y|N_o = n_o\} = \begin{cases} 1, & \text{for } y = 0 \text{ if } n_o \leq 2 \\ \binom{n_o - 2}{y} p_s^y (1-p_s)^{n_o-y-2}, & \text{for } 0 \leq y \leq n_o - 2 \text{ if } 3 \leq n_o \leq F \\ \binom{F-2}{y} p_s^y (1-p_s)^{F-y-2}, & \text{for } 0 \leq y \leq F-2 \text{ if } n_o > F. \end{cases} \tag{4.9}$$

Event 1 occurs when at least one common one-hop neighbor of the $s - d$ pair successfully receive the packet from the source node, i.e., $Y > 0$. Given $N_o = n_o$, the probability of *Event 1* occurrences is

$$\Pr\{E_1|N_o = n_o\} = 1 - \Pr\{Y = 0|N_o = n_o\}. \tag{4.10}$$

From (4.3), (4.9), and (4.10), the probability of *Event 1* occurrences can be derived as

$$\Pr\{E_1\} = \sum_{n_o=3}^{F} \left(1-(1-p_s)^{n_o-2}\right) \frac{(1.5\rho R)^{n_o} e^{-1.5\rho R}}{n_o!} + \left(1-(1-p_s)^{F-2}\right) \left(1 - \sum_{n_o=0}^{F} \frac{(1.5\rho R)^{n_o} e^{-1.5\rho R}}{n_o!}\right). \tag{4.11}$$

4.2.5.2 Existence of Unreserved Time Slots (Event 2)

For nodes sharing a same time frame and belonging to a same THS, an unreserved time slot for one node is unreserved for all of them. Hence, a potential helper node cooperates an $s-d$ pair if there exists at least one unreserved time slot in the frame belonging to the corresponding THS. *Event 2* occurs if there exists at least one unreserved time slot in the frame, which is being shared by the source, destination, and potential helper nodes. From (4.7), we have

$$\Pr\{E_2\} = \Pr\{U > 0\} = \sum_{u=1}^{F-1} \frac{(2\rho R)^u e^{-2\rho R}}{u!}. \tag{4.12}$$

From (4.8), (4.11), and (4.12), the probability of cooperation, p_{coop}, can be calculated.

4.2.6 *Benefits of Cooperation*

Note that the selection of a helper node by a destination node and initiation of a cooperation do not guarantee a successful cooperative relay transmission. Cooperation is beneficial only if the helper node successfully relays a packet to the destination node during cooperative relay transmission. With the introduction of node cooperation, transmission is successful if either direct transmission between the $s-d$ pair or cooperative relay transmission from the helper node to the destination node is successful. Hence, the probability of a successful transmission with cooperation, denoted as p_s^{coop}, between an $s-d$ pair, is given by

$$p_s^{coop} = p_s + p_s(1-p_s)p_{coop}. \tag{4.13}$$

4.3 Throughput Analysis

In this section, we derive close-form expressions for throughput and throughput gain of the proposed CAH-MAC.

4.3.1 Expected Number of Successful Time Slots

In D-TDMA based MAC, the number of successful time slots per frame is an indication of its ability to handle channel errors. If a MAC protocol is robust to a relatively poor channel condition, it can achieve a higher number of successful time slots in a frame. A time slot is successful only if the transmitted packet does not collide with packets from other nodes in the THS and the received power at the target designation node is not smaller than the threshold value. As discussed in Sect. 4.2.3, the probability of successful transmission during a time slot is p_s. Thus, given $U = u$, the number of successful time slots in a given frame, denoted as X, follows a binomial distribution with parameters $(F - u, p_s)$ and its conditional pmf is given by

$$\Pr\{X = x|U = u\} = \binom{F-u}{x} p_s^x (1 - p_s)^{F-u-x}, \qquad x = 0, 1, 2, \ldots, F - u. \tag{4.14}$$

Consequently, the expected value of X given $U = u$ is

$$E[X|U = u] = (F - u)p_s. \tag{4.15}$$

From (4.7) and (4.15), the expected number of successful time slots in a frame, $E[X]$, can be written as

$$E[X] = p_s \sum_{u=1}^{F-1} (F - u) \frac{(2\rho R)^{F-u} e^{-2\rho R}}{(F - u)!} + p_s F \left(1 - \sum_{u=1}^{F-1} \frac{(2\rho R)^u e^{-2\rho R}}{u!}\right). \tag{4.16}$$

Similarly, with the cooperation, the expected number of successful time slots in a frame as in (4.16) changes to

$$
\begin{aligned}
E[X_{coop}] = p_s^{coop} \sum_{u=1}^{F-1} (F-u) \frac{(2\rho R)^{F-u} e^{-2\rho R}}{(F-u)!} \\
+ p_s^{coop} F \left(1 - \sum_{u=1}^{F-1} \frac{(2\rho R)^u e^{-2\rho R}}{u!}\right)
\end{aligned}
\tag{4.17}
$$

where X_{coop} is a random variable to denote the number of successful time slots in a frame with cooperation enabled transmissions.

4.3.2 Throughput and Throughput Gain

Here, we define throughput as the fraction of successful time slots over the total number of time slots per frame, F. Let σ and σ_{coop} denote the throughput of ADHOC MAC and CAH-MAC respectively. We have

$$
\sigma = \frac{E[X]}{F} \tag{4.18}
$$

and

$$
\sigma_{coop} = \frac{E[X_{coop}]}{F}. \tag{4.19}
$$

Furthermore, the normalized throughput gain achieved by CAH-MAC over ADHOC MAC is given by

$$
\sigma_{gain} = \frac{\sigma_{coop} - \sigma}{\sigma}. \tag{4.20}
$$

4.4 Reliability Analysis

In this section, we develop a mathematical model to study the transmission reliability of the CAH-MAC protocol in terms of packet transmission delay and packet dropping rate.

4.4.1 Packet Transmission Delay

The packet transmission delay is defined as the number of frames that is required to successfully transmit a packet to the target destination node. Upon a transmission failure, a source node attempts to retransmit the packet until it successfully reaches the destination node. In the system under consideration, the probability of successful transmission during a time slot depends only on channel characteristics. Thus, the number of retransmission attempts is independent of the probability of transmission collisions and follows a geometric distribution [8, 9]. Let random variables M and M_{coop} denote the packet transmission delay of ADHOC MAC and CAH-MAC respectively. Hence, M follows a geometric distribution with parameter p_s and its pmf is given by

$$\Pr\{M = i\} = (1 - p_s)^{i-1} p_s, \quad i = 1, 2, 3, \ldots \tag{4.21}$$

Similarly, M_{coop} follows a geometric distribution with parameter p_s^{coop} and its pmf is given by

$$\Pr\{M_{coop} = i\} = (1 - p_s^{coop})^{i-1} p_s^{coop}, \quad i = 1, 2, 3, \ldots \tag{4.22}$$

Consequently, the expected values of M and M_{coop} are given by

$$E[M] = \frac{1}{p_s} \tag{4.23}$$

and

$$E[M_{coop}] = \frac{1}{p_s^{coop}} \tag{4.24}$$

respectively.

4.4.2 Packet Dropping Rate

When a source node fails to deliver a packet to the target destination node within the predefined time limit, it drops the packet from its buffer memory. In the system under consideration, we consider the retransmission time limit in terms of the number of frames, referred as the maximum transmission limit and denoted as M_{max}. Thus, a packet is retransmitted, either directly from a source node or through a helper node, only for a maximum of M_{max} frames. For a given M_{max} value, the packet dropping rate of ADHOC MAC, denoted as Ω, is given by

$$\Omega = 1 - \sum_{i=1}^{M_{max}} (1 - p_s)^{i-1} p_s. \tag{4.25}$$

With the cooperation enabled transmission, packet dropping rate is given by

$$\Omega_{coop} = 1 - \sum_{i=1}^{M_{max}} (1 - p_s^{coop})^{i-1} p_s^{coop} \tag{4.26}$$

where Ω_{coop} denotes the packet dropping rate of CAH-MAC.

In the next section, we present numerical results to validate the close-from expressions obtained for throughput and reliability analysis.

4.5 Numerical Results

Computer simulations are performed in MATLAB with parameters given in Table 4.1. Five hundreds vehicles are distributed along a road segment following the Poisson distribution.[2] Vehicle densities, ρ_l (vehicle per kilometer), are kept equal in all the lanes, hence $\rho = L\rho_l$. To obtain a simulation result, 200,000 different frames form the total of 40 different network topologies are simulated. Throughput, throughput gain, packet transmission delay and packet dropping rate of CAH-MAC are obtained in comparison with ADHOC MAC for several different networking scenarios.

First, we study the effect of the exponentially distributed inter-vehicular distance assumption on validity of the performance analysis. Figure 4.6 shows the throughput of CAH-MAC and ADHOC MAC obtained from simulations with minimum safety distance, denoted by r_0, between adjacent vehicles in a lane, and the numerical results as in (4.18) and (4.19). It is observed that the analytical results with $r_0 = 0$ match well with the simulation results for both ADHOC MAC and CAH-MAC. It can be observed that the difference in throughput values from numerical calculation with $r_0 = 0$ and simulations with non-zero r_0 values is not significant. As a result, in the following, we present numerical results under assumption $r_0 = 0$.

Table 4.1 Simulation parameters

Parameter	Value
Transmission range (R)	200 and 300 m
Number of time slots per frame (F)	40, 50, 60 and 80
Vehicle density per lane (ρ_l)	10, 20, 30 and 50 vehicle/kilometer
Maximum transmission limit (M_{max})	1, 5 and 10 frames
Channel characteristics (p)	[0,1]
Number of lanes (L)	2
Width of a lane (w_l)	5 m

[2] A road segment with two lanes is considered. A line represents a lane that is 5 m wide. Vehicles are represented by points on the lines.

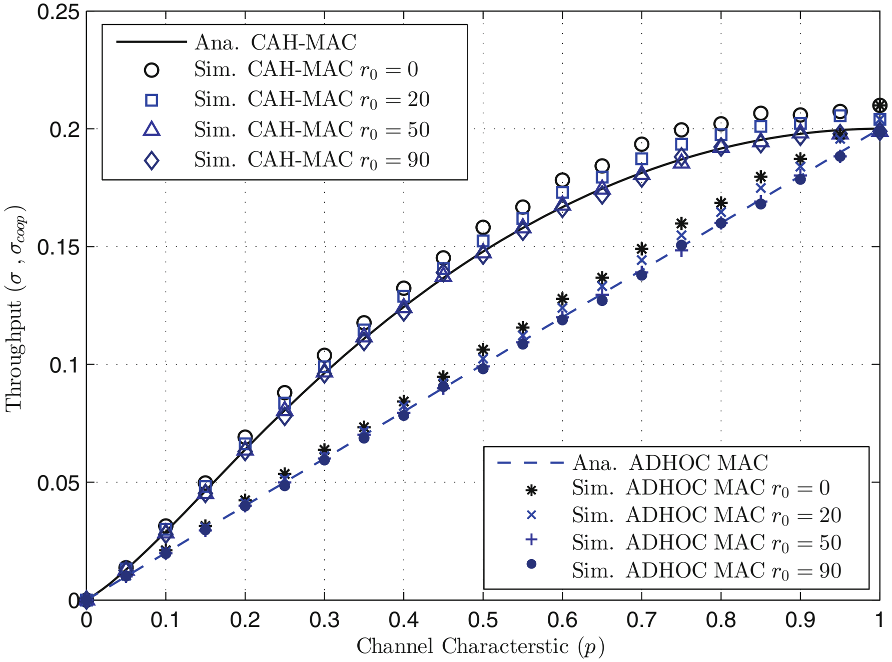

Fig. 4.6 Throughput comparison with and without a minimum separation distance (r_0) for $\rho_l =$ 10 vehicles/km, $R = 300$ m, and $F = 60$ time slots [2]

Figures 4.7–4.9 show the throughput of CAH-MAC and ADHOC MAC in different networking conditions. With an introduction of node cooperation, in general, CAH-MAC achieves higher throughput than ADHOC MAC. It can be seen from Fig. 4.7 that the throughputs are proportional to the vehicle density per lane (ρ_l). The smaller the density value, the smaller average number of THS members sharing a frame. A smaller number of THS members increases the number of unreserved time slots in a frame, which has a negative effect on the throughput. Unreserved time slots are left unused in ADHOC MAC; however in CAH-MAC, the introduction of a node cooperation reduces transmission failure by utilizing unreserved time slots. Thus, it can be observed from Fig. 4.8 that the throughput increases with an increase in the transmission range R. For the given vehicle density, the average number of THS members increases with an increase in R, which results in more efficient utilization of available time slots in each frame. Figure 4.9 shows the effect of the number of time slots per frame F on the throughput. For the given vehicle density and transmission range, i.e., for a given average number of THS members sharing a frame ($2\rho R$), the throughput decreases with an increase in F. This is due to the fact that, for a given number of THS members sharing a frame, an increase in F increases the number of unreserved time slots, which decreases the throughput. Figures 4.7, 4.8 and 4.9 show that, in general, for the same p value under a similar networking condition, throughput of CAH-MAC is more

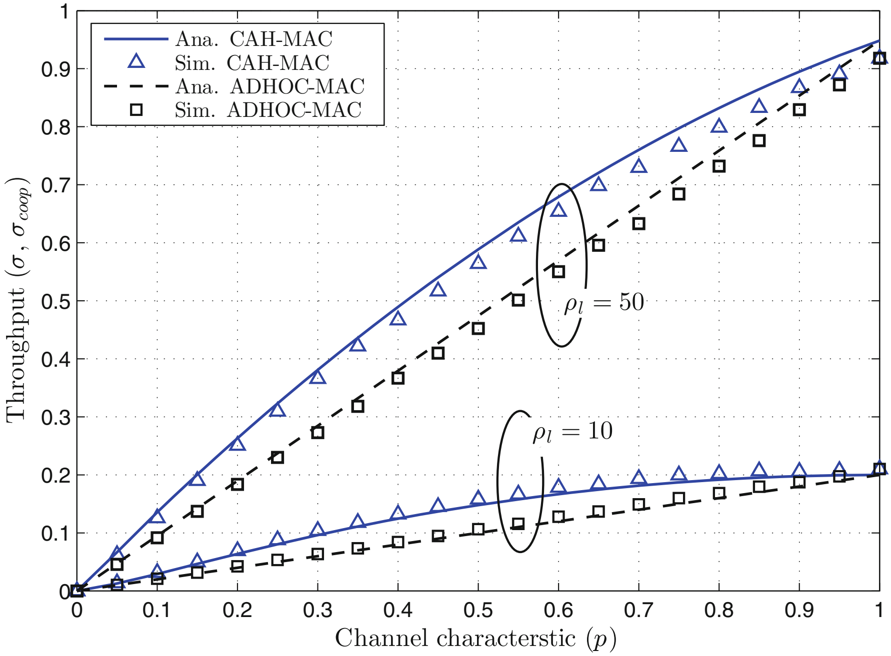

Fig. 4.7 Throughput of ADHOC MAC and CAH-MAC with $R = 300$ m and $F = 60$ time slots (ρ_l is in vehicle per kilometer) [2]

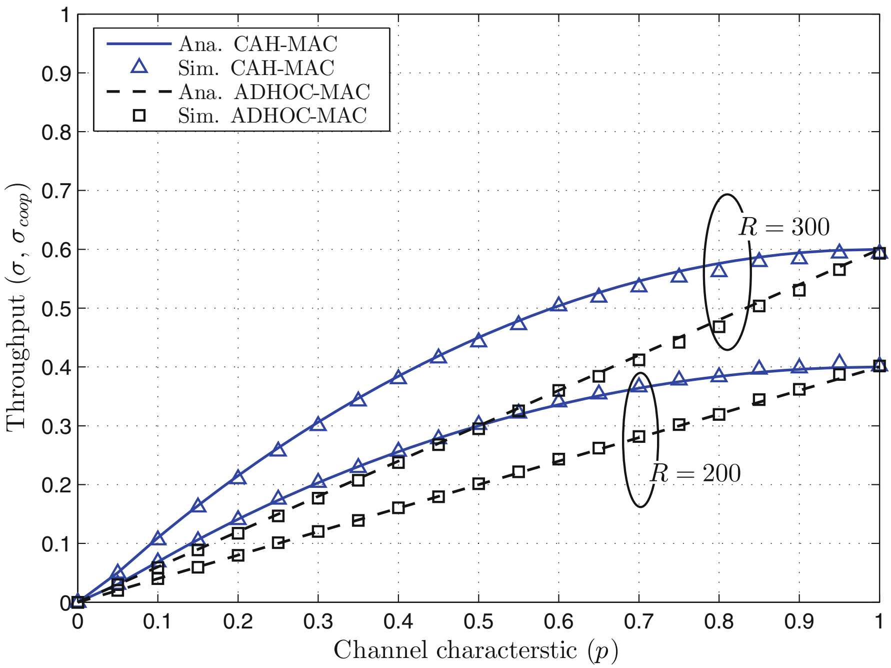

Fig. 4.8 Throughput of ADHOC MAC and CAH-MAC with $\rho_l = 30$ vehicle per kilometer and $F = 60$ time slots [2]

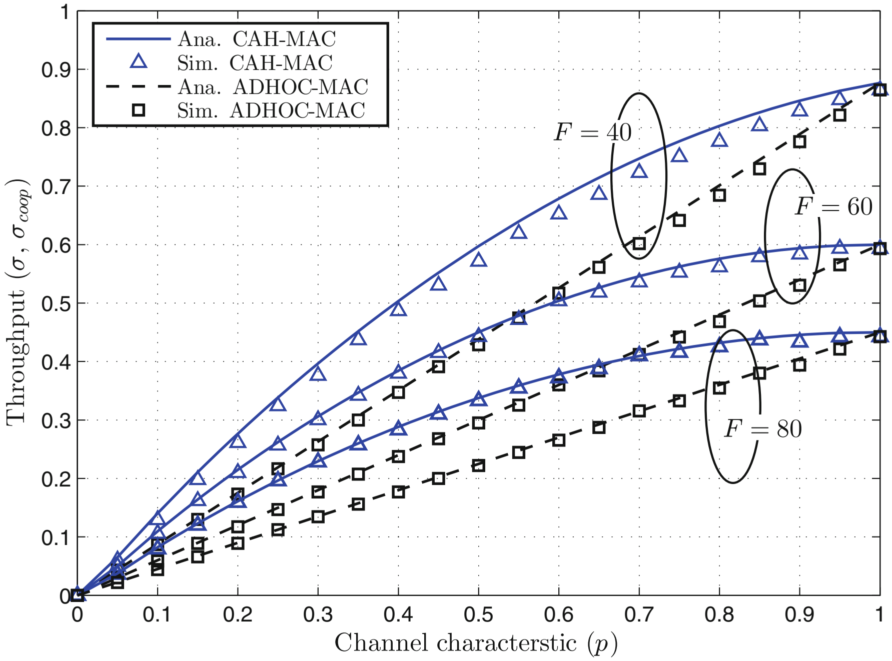

Fig. 4.9 Throughput of ADHOC MAC and CAH-MAC with $\rho_l = 30$ vehicle per kilometer and $R = 300$ m [2]

than that of ADHOC MAC. Moreover, the throughput improvement due to node cooperation increases as the channel quality improves from a very poor condition (i.e., small p value). As the channel quality improves, the probability of successful cooperative relay transmission, as well as cooperation gain, increases. If the channel quality improves further, the probability of successful direct transmission increases, reducing the needs for node cooperation and resulting to a smaller throughput gain.

Figure 4.10 shows the normalized throughput gain of CAH-MAC over ADHOC MAC in several networking scenarios. As ρ and R values increase, the number of helper nodes increases, which ultimately increases the cooperation gain. It can be observed that the throughput gains are the same for parameter pairs [$R = 200$ m, $\rho_l = 30$] and [$R = 300$ m, $\rho_l = 20$]. This is because, in both cases, the average number of THS members are the same (i.e., $2\rho R \simeq 24$). When the number of THS members is large as compared with F, the throughput gain decreases. For example, when $R = 300$ m and $\rho_l = 50$, the average number of THS members ($2\rho R = 60$) is the same as F, which results in a smaller throughput gain than that in the other cases. Furthermore, the throughput gain reaches its peak at a certain p value and starts decreasing as p further increases. With a small p value, the cooperation gain is not significant as helper nodes suffer from channel errors. With a moderate p value, when direct transmissions suffers from channel errors, node cooperation has a high probability to deliver the packet to the destination node.

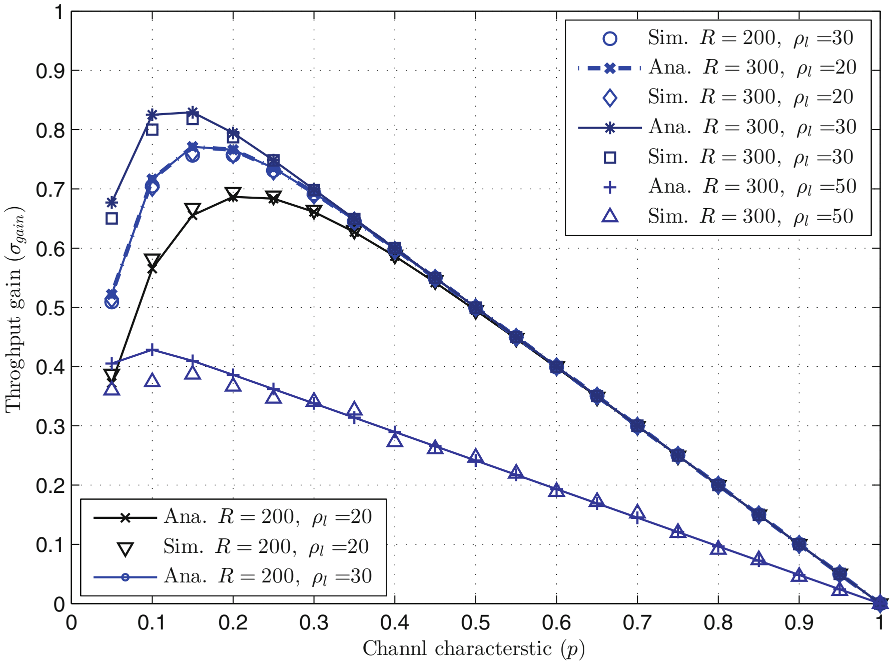

Fig. 4.10 Throughput gain of CAH MAC over ADHOC MAC with $F = 60$ time slots (ρ_l is in vehicle per kilometer) [2]

The probability of successful direct transmissions increases with a larger p value and, hence, cooperation is not required with successful direct transmission. From Fig. 4.10, it can be seen that the throughput gain increases with an increase in R and ρ_l values when $F \gg 2\rho R$. As channel quality improves (i.e., for $p > 0.4$), the throughput gain decreases linearly with p, irrespective of R and ρ_l values. In such a case, it is very likely that at least one common neighboring node of an $s - d$ pair successfully receives a packet from the source and there are unreserved time slots to perform cooperative relay transmission, resulting in $p_{coop} \simeq 1$. From (4.20), as the throughput gain depends only on p_s ($\sigma_{gain} \simeq 1 - p_s$), it does not change with R and/or ρ_l as long as $F > 2\rho R$, but reduces linearly with p_s ($= p$).

Figure 4.11 shows the average packet transmission delay (PTD) of CAH-MAC and ADHOC MAC in different networking conditions. It can be observed that the PTD of CAH-MAC is almost reduced by 40% in a poor channel condition (for $p \leq 0.25$) as compared with that of ADHOC MAC when $R = 200$ m. However, when $R = 300$ m, reduction in PTD is only about 20%. This is because the benefit of node cooperation is significant when there are a moderate number of THS members as compared with F, such that the number of potential helper nodes and unreserved time slots are sufficient to perform cooperative relay transmission. When $R = 300$ m, the total number available time slots is comparable with the

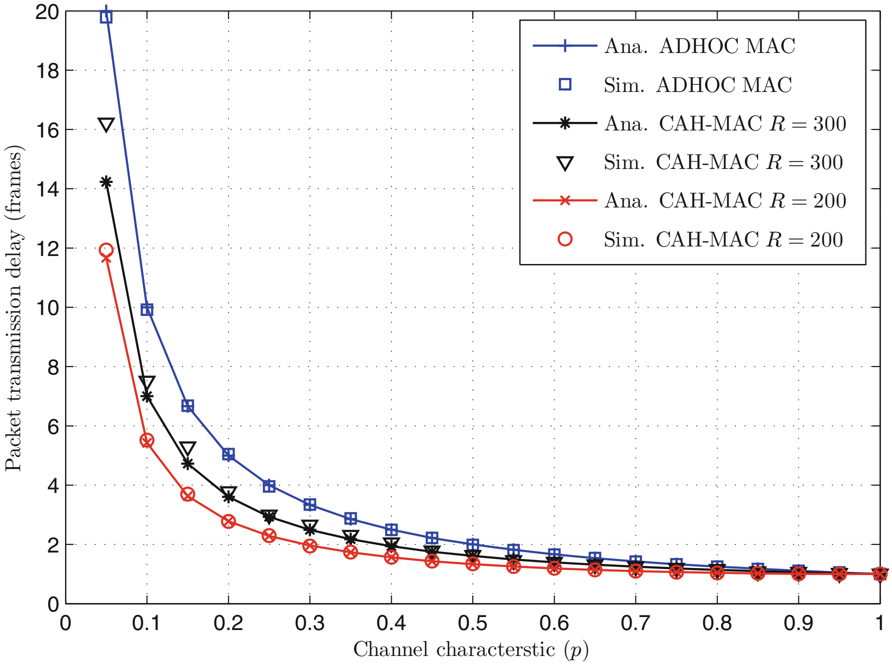

Fig. 4.11 Average packet transmission delay of ADHOC MAC and CAH-MAC with $\rho_l = 50$ vehicle per kilometer and $F = 60$ time slots [1]

average number of THS nodes sharing a frame, i.e., ($2\rho R = 60$), resulting in a fewer unreserved time slots to perform cooperative relay transmission and a smaller the p_{coop} value. Hence, a fewer of unreserved time slots for the cooperative relay transmission results in a higher packet transmission delay for $R = 300$ m. As p increases, the delay improvement starts to decrease. With the improvement in the channel condition (i.e., $p \geq 0.85$), the probability of a successful direct transmission increases. Consequently, the gap between PTD for both protocols decreases as the channel condition improves.

Figures 4.12, 4.13 and 4.14 show packet dropping rate for CAH-MAC and ADHOC MAC in various networking conditions. It is observed that, for a given channel conditions, the packet dropping rate of CAH-MAC is less than that of ADHOC MAC. However, the gap between the packet dropping rate increases as the channel condition improves in a similar networking condition, i.e., the same p_{coop} value. Hence, the gap is higher when $R = 200$ m than that when $R = 300$ m. For the same channel condition, the larger the M_{max} value, the larger the gap between the packet dropping rate of two protocols. This is due to the fact that, upon a transmission failure, in CAH-MAC, the helper node retransmits a packet in an unreserved time slot. Hence, with a larger M_{max}, a node in CAH-MAC gets more

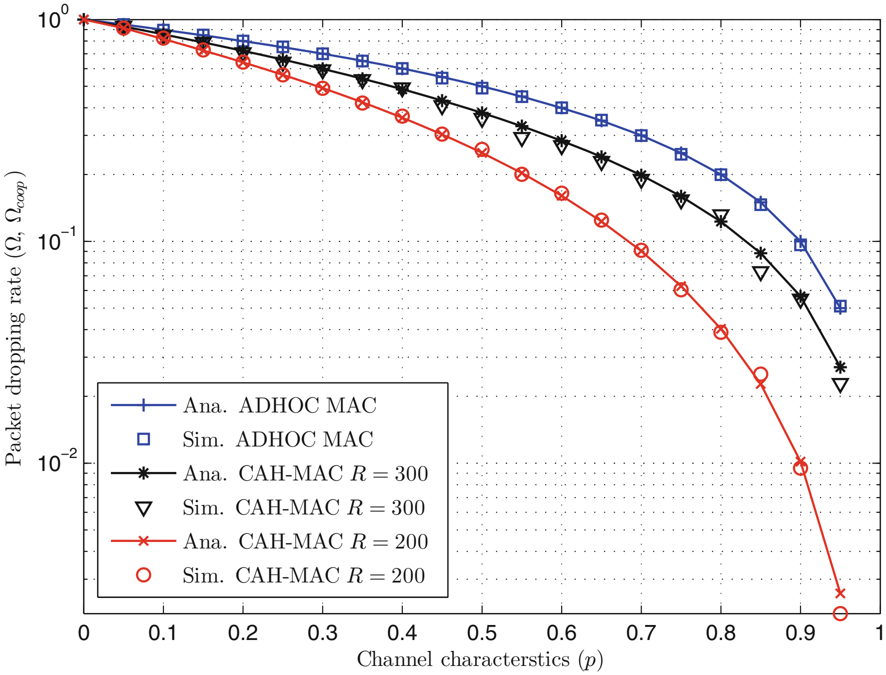

Fig. 4.12 Packet dropping rate of ADHOC MAC and CAH-MAC with $M_{max} = 1$ frame, $\rho_l = 30$ vehicle per kilometer and $F = 60$ time slots [1]

chances to retransmit a packet than that in ADHOC MAC and with a low M_{max} value. The increase in retransmission limit increases the probability of successful packet delivery to the destination node, preventing a packet from being dropped from the buffer memory.

It can be seen from Figs. 4.7–4.14 that, at two extreme channel conditions, i.e., when $p = 0$ and 1, both protocols perform equally. When $p = 0$, channel is in a very poor condition and all transmissions fail due to channel errors; thus there are no potential helper nodes to perform cooperative relay transmission. On the other hand, at $p = 1$, channel is in a very good condition and all packets reach to the destination node directly from the source node; thus node cooperation is not needed. Thus, when $p = 0$ and $p = 1$, the performance of CAH-MAC and ADHOC MAC is the same, resulting in no performance gain. Node cooperation is beneficial as p increases from zero, such that an $s - d$ pair can get potential helper nodes upon a transmission failure. Moreover, simulation results in Figs. 4.7, 4.8, 4.9, 4.10, 4.11, 4.12, 4.13 and 4.14 match well with the analytical results, which validates the close-form expressions obtained in Sects. 4.3 and 4.4.

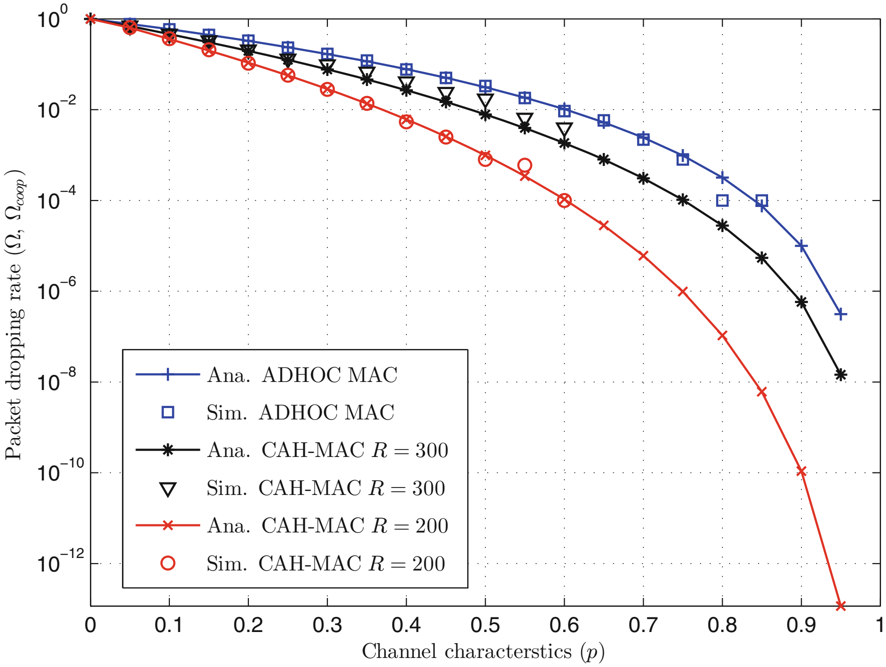

Fig. 4.13 Packet dropping rate of ADHOC MAC and CAH-MAC with $M_{max} = 5$ frames, $\rho_l = 30$ vehicle per kilometer and $F = 60$ time slots [1]

4.6 Summary

In this chapter, we present a link-layer node cooperation scheme for VANETs, referred to as Cooperative ADHOC MAC (CAH-MAC). In CAH-MAC, neighboring nodes cooperate to utilize unused time slots to retransmit failed packets. Throughput improvement is achieved by using idle time slots that are wasted in the absence of node cooperation. In addition, as a packet is retransmitted earlier by a helper node, transmission delay and packet dropping rate are reduced. Through mathematical analysis and simulation, we show that CAH-MAC increases the successful packet transmission probability. Accordingly, system throughput and transmission reliability improve due to node cooperation. In this chapter, we have not considered relative mobility among nodes. Effects of dynamic network topology changes due to the relative mobility and a more realistic link model on the performance of CAH-MAC are discussed in the next chapter.

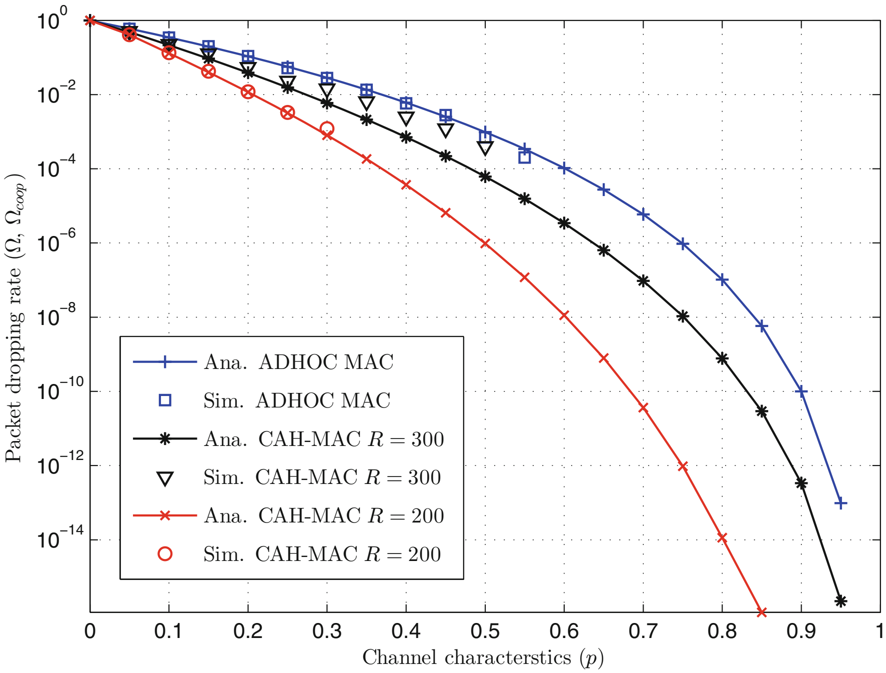

Fig. 4.14 Packet dropping rate of ADHOC MAC and CAH-MAC with $M_{max} = 10$ frames, $\rho_l =$ 30 vehicle per kilometer and $F = 60$ time slots [1]

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Chapter 5
Enhanced Node Cooperation

Chapter 4 describes Cooperative ADHOC MAC (CAH-MAC) that exploits benefits of node cooperation in D-TDMA MAC for VANETs. Performance evaluation of the CAH-MAC are carried out for the case with negligible relative mobility among nodes. With the relative node mobility and channel fading, transmission failures occur, due to the transmission collisions and/or channel errors, which force a node to release its time slot and seek for a new one (to be discussed). Transmission collisions occur, refereed to as *cooperation collisions*, when a node (seeking a time slot) accesses an unreserved time slot selected for cooperative relay transmission. Consequently, cooperation opportunities and time slot reservation attempts fail, and disruption in D-TDMA MAC operations takes place due to cooperation collisions. Thus, the existing node cooperation scheme must be improvised to avoid cooperation collisions and efficiently utilize unreserved time slots to perform either cooperative relay transmissions or time slot reservations.

In this chapter, we present an improvised CAH-MAC with a collision avoidance scheme, referred to as *enhanced CAH-MAC* (eCAH-MAC) [1, 2]. In eCAH-MAC, cooperative relay transmission is suspended if there is (are) any transmission attempt(s) from the one-hop node(s) of the destination and/or helper nodes, avoiding cooperation collision. Cooperative relay transmission is performed only if the destination and helper nodes do not detect time slot reservation attempt in their one-hop neighborhood.

Through mathematical analysis and simulations, we show that the proposed collision avoidance scheme increases the utilization of unreserved time slots by either allowing them to be reserved by nodes seeking their own time slots or using them to perform cooperative relay transmissions, without disrupting the D-TDMA MAC normal operations. Furthermore, through extensive simulations we study the performance of eCAH-MAC in the presence of relative vehicle mobility over a generalized Nakagami channel. A real highway is replicated using PTV VISSIM [3], a microscopic multi-modal traffic flow simulator, to generate vehicle mobility

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traces. Such mobility traces are used to simulate and evaluate the performance of the newly proposed eCAH-MAC, in comparison with CAH-MAC and ADHOC MAC.

5.1 System Overview

This section describes the system model and necessary assumptions for tractability in establishing the analytical framework. We mainly focus on the transmission channel and time slot access mechanism in the system model.

5.1.1 Channel Model

We consider a generalized Nakagami-m channel with correlated amplitudes, which represents small scale fading in vehicular communication and reflects a realistic driving environment [4]. For the Nakagami-m channel, the probability density function (pdf) of the received power, γ_r, by a receiving node at r meters from a transmitting node follows a gamma distribution and is given by Simon and Alouini [5]

$$f_{\gamma_r}(x) = \left(\frac{m}{\bar{\gamma}_r}\right)^m \frac{x^{m-1}}{\Gamma(m)} e^{\left(-m\frac{x}{\bar{\gamma}_r}\right)} \tag{5.1}$$

where $\Gamma(\cdot)$ is the gamma function, $\bar{\gamma}_r = \frac{P_t C}{r^\alpha}$ is the average received power at distance r from the transmitting node, α is the path-loss exponent, $C = G_t G_r \left(\frac{c}{4\pi f_c}\right)^2$ is a constant, G_t and G_r are antenna gains at the transmitter and receiver respectively, $f_c = 5.9\,\text{GHz}$ is the carrier frequency, $c = 3 \times 10^8$ m/s is the speed of light, and m is a distance dependent shape parameter of the Nakagami-m channel, which is given as [6]

$$m = \begin{cases} 3, & r \leq 50 \\ 1.5, & 50 < r \leq 100 \\ 1, & r > 100. \end{cases} \tag{5.2}$$

For a system where vehicles are moving in a one-way road with the same average speed, the auto-correlation function of received signals can be approximated by Jake's model [7, 8]. Furthermore, such approximation is validated with simulation for a vehicular environment [9]. Thus, for the system under consideration, the amplitude correlation coefficient of a signal received, denoted as ϱ, at two different time instances separated by τ seconds, can be realized by Jake's model as well and is given by Lopez-Martinez et al. [10]

$$\varrho = J_0^2(2\pi f_d \tau) \tag{5.3}$$

where, $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind and f_d is the average Doppler spread. The normalized fading rates, which is the product of the average Doppler spread and sample time, i.e., $f_d\tau$, greatly defines the nature of a time-varying channel [11]. On the other hand, the average Doppler spread, f_d, of the time-variant vehicle-to-vehicle (V2V) channel depends on the effective speed, denoted as v_{eff}, and is given by

$$v_{eff} = \sqrt{v_r^2 + v_t^2} \tag{5.4}$$

where v_r and v_t are the velocities of receiver and transmitter of a link.

Furthermore, the relationship of f_d with v_{eff} depends on the driving environment where the receiver and transmitter nodes are traveling, such as highway, rural and suburban environments. Scatterers, both mobile (e.g., pedestrians, passing vehicles) and stationary (e.g., foliage, buildings), are unavoidable in such driving environments. The presence of such scatterers greatly affects the Doppler spread and eventually the channel variations [12]. In [13], a close-form expression of Doppler spread is derived specifically for the V2V channel, through experiments at 5.9 GHz, in terms of the effective velocity and environment dependent parameters and is given by

$$f_d = \frac{\theta}{\lambda\sqrt{2}} v_{eff} + o \tag{5.5}$$

where θ and o are environment dependent parameters of the V2V channel, referred to as slope and offset respectively, whose values for different driving environments are given in Table 5.3 in Sect. 5.5.

5.1.2 Cooperation Collisions and Release of Time Slots

In each frame, a node has information to transmit to a target destination node along with the frame information. Thus, in its own time slot, a node transmits a packet that consists of FI, PH, payload data, CRC and may include its cooperation decisions via COH (as discussed in Sect. 4.1). A node embeds IDs of its OHS nodes in its FI, if it successfully received the packet in the previous frame. Hence, successful reception of FIs helps a node to extract its neighborhood information such as IDs of the one-hop neighboring nodes and their corresponding time slots. Also, the FI can be used to detect transmission failures due to poor channel conditions or transmission collisions (as discussed in Sect. 4.1.1). A node releases or continues using its time slot based on the FIs received from its OHS neighbors. Upon failing to detect its ID in FIs from at least one of its OHS member nodes, a node releases its time slot. However, to avoid unnecessary loss of time slots, the node does not consider FI from (new one-hop) nodes that are not in its OHS. It update its OHS after it successfully receives FIs from new one-hop nodes. Thus, in the network, there are nodes with and/or without their own time slots. Nodes without their own time slots and seeking for one are referred to as contending nodes, as they contend for time slots in the corresponding two-hop neighborhood. Remaining nodes which have their own time slots to access the channel are referred to as resident nodes, as they continue to be a resident of the corresponding two-hop neighborhood.

Channel fading and relative node mobility result in transmission failures. Due to such transmission failures, a node may fail to reserve or retain a time slot. Consequently in the next frame, contending nodes remain as contending nodes, and some resident nodes may release their time slots and become new contending nodes. With cooperation enabled transmission and the presence of contending nodes, cooperation collisions may occur in D-TDMA MAC during unreserved time slots selected for node cooperation. Cooperation collisions occur during unreserved time slots between reservation packets from contending nodes and cooperative relay transmissions from helper (resident) nodes. Under such events, both cooperative relay transmission and time slot reservation fail and contending nodes have to wait longer to acquire time slots. On the other hand, most of the time, only resident nodes get an opportunity to access the channel for direct and/or cooperative relay transmission. Cooperation collisions also occur when cooperative relay transmission is performed during a time slot belonging to an resident node. For instance, if a helper node chooses an unreserved time slot, to cooperate an $s - d$ pair, which belongs to a node that just enters the two-hop distance region of the $s - d$ pair and/or helper node after scheduling the cooperative relay transmission. In such an event, transmission collision occurs between the regular transmission from the newly joined node and scheduled cooperative relay transmission.

Upon suffering from a transmission failure, either due to channel errors or transmission collision or both, a node releases its time slot and seeks a new one. Also, a node which does not have its own time slot prior to joining the network, seeks for a time slot as soon as it joins the network. Furthermore, due to the relative mobility, a node may enter a new THS where its neighboring nodes are not aware of its arrival. If the node owns an unreserved time slot, with respect to the new THS, it keeps on using it as there will not be any conflict. However, a collision occurs if the unreserved time slot is selected to perform cooperative relay transmission. By the end of each frame, a resident node may lose its time slot and/or a contending node may successfully reserve one. Consequently, a frame consists of reserved and unreserved time slots. The number of reserved (or unreserved) time slots depends on channel quality, relative mobility, and other characteristics of the networking scenarios.

5.2 Enhanced Cooperative ADHOC MAC

As discussed in the previous section, node cooperation may lead to conflicts in the form of cooperation collisions, which further result in failures in time slot acquisitions and cooperative relay transmission. To tackle such conflicts and mitigate the associate negative effects, several features, such as different packet types and a novel collision avoidance approach, are introduced in the eCAH-MAC scheme. This section describes such features which help to avoid cooperation collisions in eCAH-MAC.

5.2.1 Types of Packet Structure

In each frame, a resident node transmits a packet during its own time slot in order to exchange its FI and payload data to the one-hop nodes and target destination node respectively. In order to continue using its time slot in the consequent frames, the resident node must successfully deliver its FI to all nodes in its OHS. Moreover, when a resident node transmits a packet during an unreserved time slot to perform cooperative relay transmission, it must deliver the payload data to the target destination(s). On the other hand, a contending node must deliver its FI to all the nodes in its OHS during an unreserved time slot to successfully reserve the time slot. Note that it is not necessary to transmit the same information, with the same packet structure or fields, for the aforementioned scenarios. Based on the operations, we define three type of packets that a node can transmit during a time slot, as described below:

1. *General packet* (**Type-G**) consists of FI, PH, payload data and CRC, which is transmitted by a resident node to exchange messages to the nodes in its one-hop distance. A resident node transmits a Type-G packet to deliver its FI to the OHS nodes and payload data to the target destination node(s). Furthermore, the packet consists of cooperation header (COH) if the transmitting node decides to help an $s-d$ pair that suffers from channel errors, as discussed in Sect. 4.1.
2. *Reservation packet* (**Type-R**) consists of FI, PH and CRC, which is transmitted by contending nodes for time slot acquisitions. A contending node first reserves a time slot to access the channel using a Type-R packet (without payload data), then starts to transmit a Type-G packet to exchange FIs and payload data with its one-hop neighbor node(s) and target destination node(s) respectively, during the acquired time slot.
3. *Cooperation packet* (**Type-C**) consists of a PH, payload data and CRC, which is transmitted during an unreserved time slot to perform cooperative relay transmission by a helper (resident) node. The helper node does not transmit its FI during cooperative relay transmission. Transmission of FI during cooperative relay transmission is not necessary as the helper node has its own time slot to transmit Type-G packets embedded with FI.

Furthermore, cooperation acknowledgement (C-ACK) is transmitted by a destination node to start the cooperative relay transmission phase, which consists of the ID of the selected potential helper node, as described in Sect. 4.1.

5.2.2 Cooperation Collision Avoidance

A cooperation collision occurs if a contending node accesses an unreserved time slot selected to perform cooperative relay transmission. To avoid cooperation collisions in eCAH-MAC, cooperative relay transmission phase is delayed by a time interval, say β_1. The duration of β_1 interval should be enough for a node to sense the channel and determine whether it is idle or busy, such as the distributed inter-frame space (DIFS) in the IEEE 802.11 based MAC protocols [14]. Note that in CAH-MAC, the destination node transmits C-ACK as soon as the unreserved time slot starts, i.e., $\beta_1 = 0$ s. In eCAH-MAC, a destination node, during an unreserved time slot selected for node cooperation, waits for β_1 seconds and then transmits C-ACK only if the channel is idle during the waiting time, which is illustrated in Fig. 5.1. Accordingly, the selected helper node (whose ID is embedded in the transmitted C-ACK) transmits a Type-C packet, which consists of payload data from the source node, after a guard time after detecting its ID in the transmitted C-ACK. Note, the length of C-ACK (in bits) and guard time (in seconds) are constant. Thus, the helper node always performs cooperative relay transmission after the fixed duration from the start of a time slot, say β seconds, such that $\beta = \beta_1 + \beta_2$ as in Fig. 5.1, where β_2 corresponds to the transmission time of C-ACK plus the guard time.

A helper node performs cooperative relay transmission by transmitting a Type-C packet to the target destination node that failed to receive a packet directly from a source node. As a Type-C packet does not include FI, the absence of FI compensates for the delayed time of cooperative relay transmission phase and does not affect the normal operation of D-TDMA. Furthermore, the transmission of C-ACK from a destination node helps to avoid collision among helper nodes during the cooperative relay transmission, as described in Sect. 4.1.

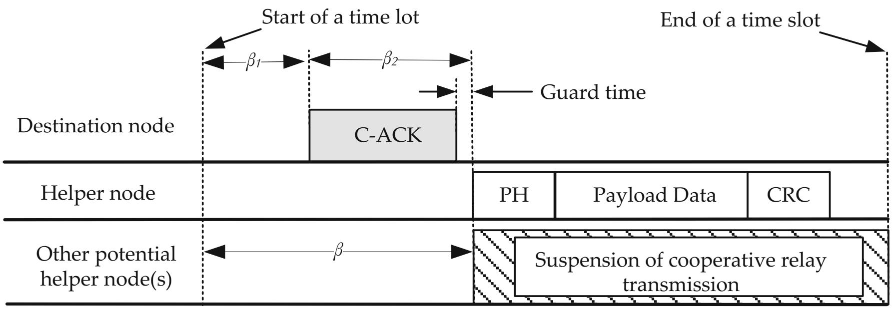


Fig. 5.1 Cooperative relay transmission in eCAH-MAC during an unreserved time slot [2]

A contending node may access the channel during the unreserved time selected for cooperation. When the destination node detects transmission(s) from the contending node(s), it suspends the cooperative relay transmission phase by not transmitting the C-ACK. After failing to receive C-ACK within β seconds from the start of a time slot, the helper node also suspends cooperative relay transmission. Thus, delaying the cooperative relay transmission phase helps a destination node to detect transmission from contending nodes and avoid cooperation collisions. However, collision occurs if a contending node and the destination node are not in each others' one-hop distance but in two-hop distance. In such a scenario, the destination node does not sense the transmission from the contending node and transmits C-ACK, resulting in a collision at their common one-hop nodes including helper node. In order to avoid such collisions, both the helper and destination nodes must suspend their respective transmissions, i.e., transmissions of C-ACK and Type-C packet respectively. One possible way to do so is by using energy-burst or channel jamming signal, also known as black-burst [15]. Black-burst can be used in wireless networks to inform neighboring nodes about the channel usage and to avoid transmission collisions by forcing neighboring nodes to delay or suspend their transmissions [16, 17].

In eCAH-MAC, a contending node uses black-bursts to inform destination and/or helper nodes about its intention to perform reservation attempt followed by the transmission of a Type-R packet. The contending node transmits a black-burst of β seconds. If the destination node is in the one-hop neighborhood of the contending node, it suspends the cooperative relay transmission after finding the channel busy, as illustrated in Fig. 5.2. When black-burst is transmitted by contending node(s) that is not in one-hop transmission distance of the destination node, C-ACK is transmitted by the destination node upon finding an idle channel. In such a case, the transmitted C-ACK collides with the black-burst at helper node's receiver, as illustrated in Fig. 5.3. In both scenarios, the helper node does not receive the C-ACK, due to the suspension or collisions, and consequently suspends cooperative relay transmission allowing the contending node(s) to perform time slot reservation. A contending node, on the other hand, transmits a Type-R packet, followed by the transmission of a black-burst, to reserve the corresponding time slot. Thus,

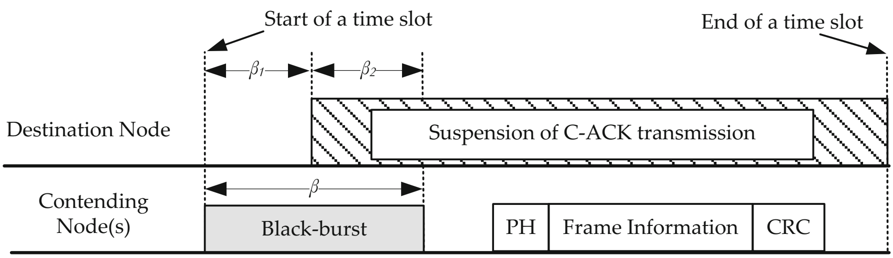


Fig. 5.2 Suspension of a cooperative relay transmission by the destination node in the presence of the contending node(s) in its one-hop distance [2]

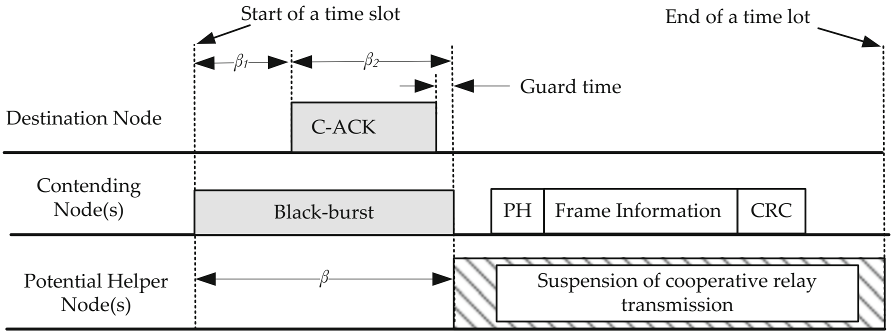


Fig. 5.3 Suspension of a cooperative relay transmission by the helper node after failing to receive C-ACK [2]

delaying the cooperative relay transmission phase and the use of a black-burst by contending node allow the destination and/or helper nodes to detect time slot reservation attempts from contending nodes and to avoid cooperation collisions. However, access collisions occur if two or more contending nodes transmit black-burst signals and their corresponding Type-R packets during the same unreserved time slot.

To summarize, cooperation collisions can be avoided by using three packet types and black bursts to reserve a time slot and suspending or delaying cooperative relay transmission phase. Consequently, unreserved time slots are efficiently utilized either to perform cooperative relay transmissions or reservations due to the avoidance of cooperation collisions. In the next section, we derive a close-form expression for the utilization of an unreserved time slot in eCAH-MAC.

5.3 Utilization of an Unreserved Time Slot

In this section we develop a mathematical model to study the effectiveness of node cooperation in utilizing time slots, without affecting the normal operations of D-TDMA MAC. As reserved time slots are used in cooperation enabled transmission in a similar manner to that without node cooperation, performance of node cooperation in eCAH-MAC must be evaluated based on how efficiently it utilizes unreserved time slots in comparison with that of D-TDMA MAC, such as ADHOC MAC. Thus, we intend to study how an unreserved time slot is utilized in the presence of node cooperation. For tractable analysis, the following assumptions are made:

1. A packet is transmitted only once by a source and/or helper nodes.
2. We do not consider the cases where a failed direct transmission does not find a helper node and/or unreserved time slot to perform cooperative relay

transmission. Performance of node cooperation due to the existence of potential helper nodes and unreserved time slots are presented in Chap. 4. Here, we focus on how node cooperation affects time slot reservation, which is one of the critical operations in D-TDMA MAC.

3. With a focus to study the effects of node cooperation in the operation of D-TDMA MAC, only the unreserved time slots selected to perform cooperative relay transmissions are considered. Unreserved time slots that are not selected for node cooperation will not be affected by cooperative relay transmission, hence such time slots are ignored in the analysis.
4. We define a parameter referred to as reserved ratio, and denoted by $\eta \in (0, 1]$, which is the ratio of the number of reserved time slots in a frame to the total number of time slots per frame, F. The η (or 1-η) value reflects the number of reserved (or unreserved) time slots and depends on channel quality, relative mobility, and other networking aspects. At the beginning of a time frame, ηF time slots are allowed to be reserved and at least $(1-\eta)F$ time slots are unreserved time slots which may be used by contending nodes to perform reservation attempts.

To derive a close-form expression for the utilization of unreserved time slots, the following events are considered which may occur during an unreserved time slot selected for cooperative relay transmission:

1. *Event* 3 (E_3): None of the contenting nodes which share the same two-hop neighborhood and frame of the helper and destination nodes attempts to access the unreserved time slot;
2. *Event* 4 (E_4): Only one contending node that shares the same two-hop neighborhood and frame of the helper and destination nodes transmits black-burst and reservation packet during the selected unreserved time slot.

Next, we derive the probability distribution functions required to obtain the probability of the aforementioned events.

5.3.1 Distribution of Node Number

Let N_C denotes the number of contending nodes in a THS. Contending node exists if the number of THS nodes is greater than ηF, i.e., if $N_T > \eta F$. In such a case, ηF nodes are resident nodes with their own time slots and the remaining $N_T - \eta F$ nodes are contending nodes seeking their own time slots. Thus, the number of contending nodes in a THS for given η can be written as

$$N_C = \begin{cases} 0, & N_T \le \eta F \\ N_T - \eta F, & N_T > \eta F. \end{cases} \tag{5.6}$$

Hence, from (4.2) and (5.6), the pmf of N_C can be written as,

$$\Pr\{N_C = n_c\} = \begin{cases} \sum_{n_t=0}^{\eta F} \dfrac{(2\rho R)^{n_t} e^{-2\rho R}}{n_t!}, & \text{if } n_c = 0 \\ \frac{(2\rho R)^{\eta F + n_c} e^{-2\rho R}}{(\eta F + n_c)!}, & n_c > 0. \end{cases} \tag{5.7}$$

Consequently, given η, the number of unreserved time slot in a time frame, U, is given by

$$U = \begin{cases} F - N_T, & N_T < \eta F \\ F - \eta F, & N_T \geq \eta F. \end{cases} \tag{5.8}$$

Note, if there are no contending nodes in a THS, i.e., if $N_C = 0$ or $N_T \leq \eta F$, unreserved time slots are not selected to perform reservation attempts. Otherwise, if $N_C > 0$ or $N_T > \eta F$, a contending node attempts to acquire an unreserved time slot. In doing so, it randomly selects one unreserved time slot among $F - \eta F$ available unreserved time slots in a frame. Thus, a contending node selects a given unreserved time slot with probability $\frac{1}{F-\eta F}$. Consequently, the probability that a contending node does not select the given unreserved time slot is $\frac{F-\eta F-1}{F-\eta F}$. Based on these probability values, the probability of occurrence of events E_3 and E_4 can be derived, which will be used to derive the required close-form expressions for utilization.

5.3.2 *Probability of Event* 3

As a contending node performs reservation only during an unreserved time slot, an unreserved time slot remains idle, if none of the contending nodes in the corresponding THS attempts to access it, i.e, if event E_3 occurs. Based on the previous discussion, given $N_C = n_c$, and $N_T = n_t$, the probability of event E_3 occurrences can be written as

$$\Pr\{E_3 | N_C = n_c, N_T = n_t\} = \begin{cases} 1, & n_t \leq \eta F \\ \left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c}, & n_t > \eta F. \end{cases} \tag{5.9}$$

Consequently, from (5.6) and (5.9), we have

$$\Pr\{E_3 | N_C = n_c\} = \begin{cases} 1, & n_c = 0 \\ \left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c}, & n_c > 0. \end{cases} \tag{5.10}$$

From (5.7) and (5.10), the probability that an unreserved time slot is not selected by contending nodes, i.e., the probability of event E_3 occurrences, can be written as

$$\Pr\{E_3\} = \sum_{n_t=0}^{\eta F} \frac{(2\rho R)^{n_t} e^{-2\rho R}}{n_t!} + \sum_{n_c>0} \left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c} \frac{(2\rho R)^{\eta F+n_c} e^{-2\rho R}}{(\eta F+n_c)!} \tag{5.11}$$

which can be further simplified to

$$\Pr\{E_3\} = \sum_{n_t=0}^{\eta F} \frac{(2\rho R)^{n_t} e^{-2\rho R}}{n_t!} + a^{-\eta F} e^{-2\rho R} \left(e^b - \sum_{n_c=0}^{\eta F} \frac{b^{n_c}}{n_c!}\right) \tag{5.12}$$

where $a = \frac{F-\eta F-1}{F-\eta F}$ and $b = 2\rho R a$.

5.3.3 *Probability of Event* 4

Event E_4 occurs if only one of the contending nodes in a THS attempts to access the unreserved time slot selected for node cooperation. Hence, given $N_C = n_c$ and $N_T = n_t$, the probability of event E_4 occurrences can be written as

$$\Pr\{E_4|N_C = n_c, N_T = n_t\} = \begin{cases} 0, & n_t \le \eta F \\ n_c \left(\frac{1}{F-\eta F}\right)\left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c-1}, & n_t > \eta F. \end{cases} \tag{5.13}$$

Consequently, from (5.6) and (5.13), we have

$$\Pr\{E_4|N_C = n_c\} = \begin{cases} 0, & n_c = 0 \\ n_c \left(\frac{1}{F-\eta F}\right)\left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c-1}, & n_c > 0. \end{cases} \tag{5.14}$$

From (5.7) and (5.14), the probability that an unreserved time slot is selected by only one contending node, i.e., the probability of event E_4 occurrences, can be written as

$$\Pr\{E_4\} = \sum_{n_c>0} n_c \left(\frac{1}{F-\eta F}\right)\left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c-1} \frac{(2\rho R)^{\eta F+n_c} e^{-2\rho R}}{(\eta F+n_c)!} \tag{5.15}$$

which can be further simplified to

$$\Pr\{E_4\} = \left(\frac{1-a}{a^{\eta F+1}}\right) e^{-2\rho R}\left[(b-\eta F)e^{b} + \sum_{n_c=0}^{\eta F-1}(\eta F - n_c)\frac{b^{n_c}}{n_c!}\right]. \tag{5.16}$$

Next, we use the probabilities of aforementioned events to derive the utilization of an unreserved time slot for ADHOC MAC, CAH-MAC and eCAH-MAC.

5.3.4 Close-Form Expressions for Time Slot Utilization

In ADHOC MAC, as cooperation is not enabled, a successful time slot reservation guarantees an efficient utilization of the unreserved time slot. In the other words, the unreserved time slot is referred to as efficiently utilized if only one contending node chooses it to acquire. Whereas if it remains unused or more than one contending nodes transmit their reservation packets, the unreserved time slot is wasted. Hence, the utilization of an unreserved time slot in ADHOC MAC, denoted as ϵ_A, can be written as

$$\epsilon_A = \Pr\{E_4\}. \tag{5.17}$$

A cooperation collision occurs if at least one contending node chooses to reserve the unreserved time slot selected to perform cooperative relay transmission. Whereas if multiple contending nodes choose the unreserved time slot to perform reservation, access collision occurs, as discussed in Sect. 3.5. Thus in CAH-MAC, an unreserved time slot selected for cooperation is considered to be efficiently utilized only if none of the contending nodes choose it to perform reservation. Hence, the utilization of an unreserved time slot in CAH-MAC, denoted as ϵ_C, can be written as

$$\epsilon_C = \Pr\{E_3\}. \tag{5.18}$$

In eCAH-MAC, in addition to successful time slot reservations, successful cooperative relay transmissions further ensure the efficient utilization of unreserved time slots. Thus, an unreserved time slot selected for cooperation is considered to be efficiently utilized if it is used to perform either cooperative relay transmission, if none of the contending node chooses it, or reservation attempt is performed by only one contending node. Hence, the utilization of an unreserved time slot in eCAH-MAC, denoted as ϵ_E, is given by

$$\epsilon_E = \Pr\{E_3\} + \Pr\{E_4\}. \tag{5.19}$$

5.4 Numerical Results

Computer simulations are performed in MATLAB with parameters given in Table 5.1. We consider free-flow node mobility as in [18] such that, at the beginning of simulation, vehicles are distributed following a Poisson distribution, along a road segment of length 10 km with three lanes.[1] The speed of vehicles follows a normal distribution,[2] with mean 100 km/h and standard deviation 20 km/h. All the vehicles move with the same speeds which are drawn at the beginning of simulation. To keep the vehicles in the simulation, vehicles exiting from one end of the road segment re-enters from the other end. Furthermore, in order to avoid any unrealistic updates of THS and OHS, and possible loss of time slots, vehicles do not break their communication links even after exiting from one end of the road segment and entering from the other end. That is, a vehicle that is at a distance r from one end of the road segment and a vehicle that is at a distance $R - r$ from the other end are allowed to communicate as if they are within each other's transmission range. Utilization of eCAH-MAC, CAH-AMC and ADHOC MAC are obtained and compared for several η values.

Figures 5.4, 5.5, and 5.6 compare the utilization with several η values. The simulation results (S) match well with the analytical results (A), which validates the close-form expressions for time slot utilization derived in Sect. 5.3. For a given average number of THS nodes, denoted by $\overline{N}_T$, a higher utilization of an unreserved time slot is achieved with a larger η value in the CAH-MAC. It is because a larger η value results in a smaller number of contending nodes and, consequently, a lesser number of reservation attempts and cooperation collisions. However, for a larger $\overline{N}_T$ value, the utilization of an unreserved time slot decreases with an increase in η value, for eCAH-MAC and ADHOC MAC. This is due to the fact that, the lesser the η value, the larger the number of contending nodes and unreserved time slots, which increases the probability of successful time slot acquisitions and consequently, the utilization of an unreserved time slots in eCAH-MAC and ADHOC MAC. With

Table 5.1 Simulation parameters [2]

Parameter	Value
Path loss exponent (α)	2, 3 and 4
Transmission power (P_t)	20 mW
Threshold received power (γ_{th})	95 dBm
Transmission range (R)	100 m
Number of time slots per frame (F)	50
Time slot duration (τ)	1 ms
Simulation time	120 s

[1] A line represents a lane that is 5 m wide and vehicles are represented by points on the lines, as in Sect. 4.5.

[2] Negative and zero velocity values are ignored while drawing the speed of a vehicle.

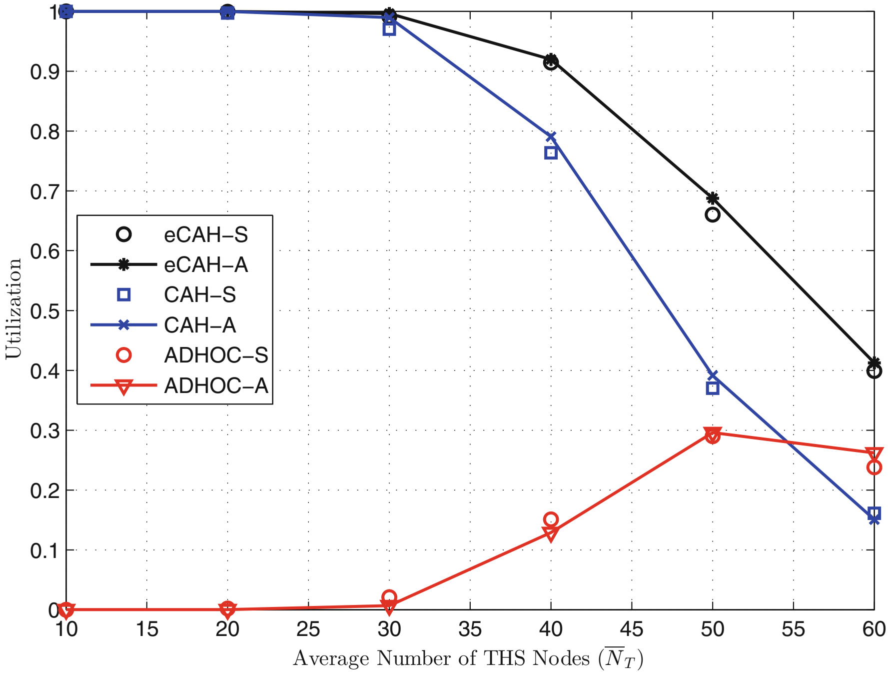


Fig. 5.4 Comparison of utilization of unreserved time slots in eCAH-MAC, CAH-MAC and ADHOC MAC with $\eta = 0.80$ [2]

an increase in the average number of THS nodes, utilization decreases when node cooperation is enabled. Thus, as the $\overline{N}_T$ value increases, the average number of contending nodes increases, increasing the number of reservation attempts. The increase in the number of reservation attempts and the number of successful time slot acquisitions improve the performance of ADHOC MAC and eCAH-MAC. However, in CAH-MAC, the increase in the number of reservation attempts decreases the performance. This is due to an increase in the number of reservation attempts which increases the probability of cooperation collisions. Similarly, CAH-MAC performs the worst as compared to ADHOC MAC and eCAH-MAC when the average number of THS nodes is high (e.g., $\overline{N}_T > 50$). At a high $\overline{N}_T$ value, the number of reservation attempts increases the number of cooperation collisions in CAH-MAC. Such an increase in the number of collisions reduces the utilization of an unreserved time slot as both time slot reservation attempt and cooperative relay transmission fail.

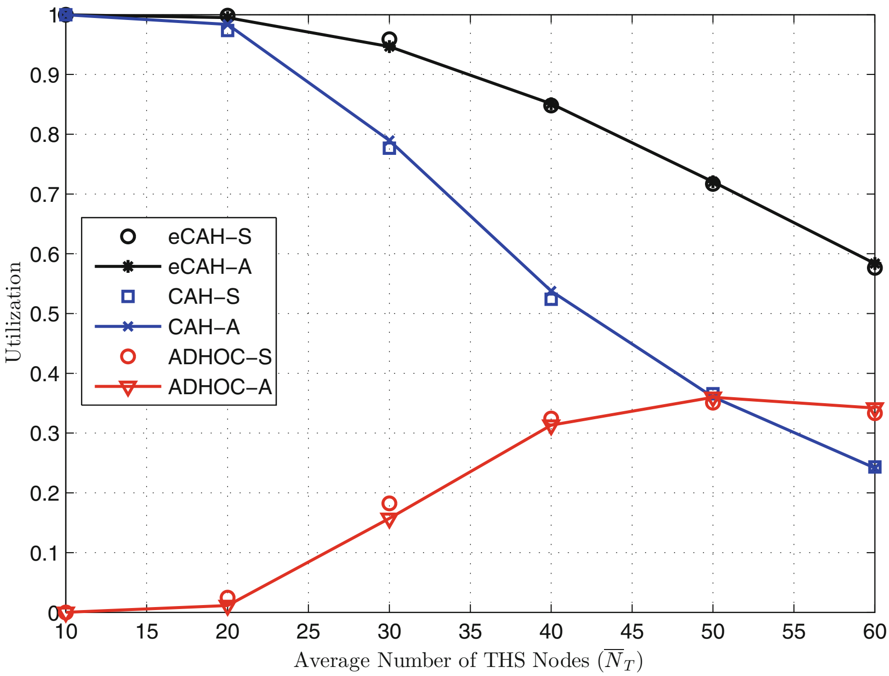


Fig. 5.5 Comparison of utilization of unreserved time slots in eCAH-MAC, CAH-MAC and ADHOC MAC with $\eta = 0.50$ [2]

5.5 Simulation Results

Computer simulations with vehicle mobility traces and Nakagami-*m* channel model are conducted to evaluate the performance of eCAH-MAC and compare it with that of CAH-MAC and ADHOC MAC. To simulate relative node mobility, we use a well-known vehicle traffic simulator PTV VISSIM [3] and MATLAB. The VISSIM simulation parameters are given in Table 5.2 (important parameters used in VISSIM simulations are discussed in Appendix B). To generate vehicle traces, a ring of highway segment with three lanes, based on a segment of Highway 401 of the province of Ontario in Canada as in Fig. 5.7a, is replicated in VISSIM. Here, the ring of road network, approximately 4 km, is formed to stop vehicles, such as cars, heavy goods vehicles (HGVs) and buses, from escaping during the simulation. Hence, the vehicles keep moving in the ring of road network and do not exit throughout the simulation. Figure 5.7b shows the snapshot of the simulated vehicles moving in the ring of road network. These vehicles follow the Wiedemann99 Car Following Model [19], to follow the headway traffic. Based on the model, appropriate decisions are made to perform lane changes, left or right turns, and to follow the vehicle in front. Road segments, speed limits, and other traffic rules are defined based on realistic observations.

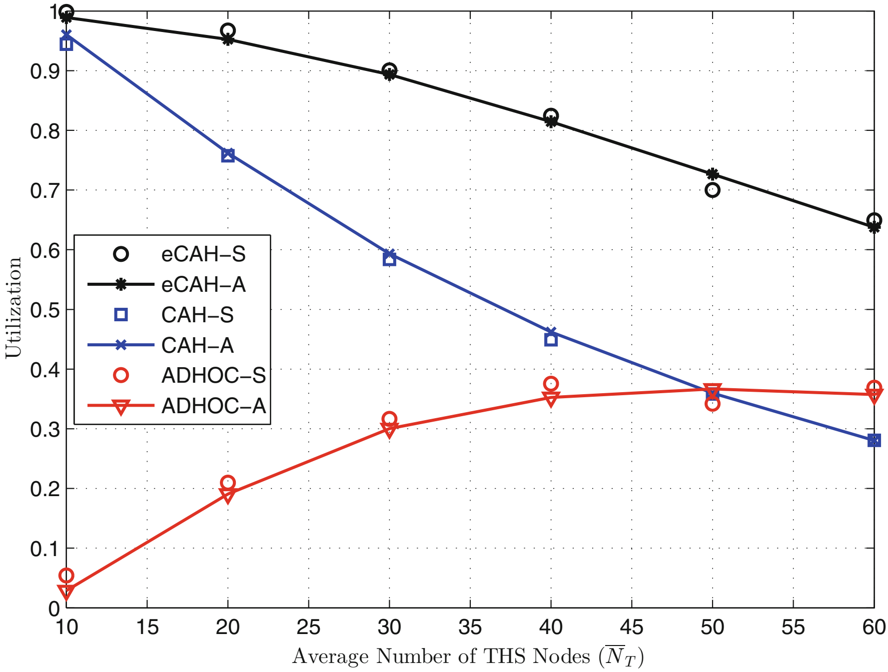


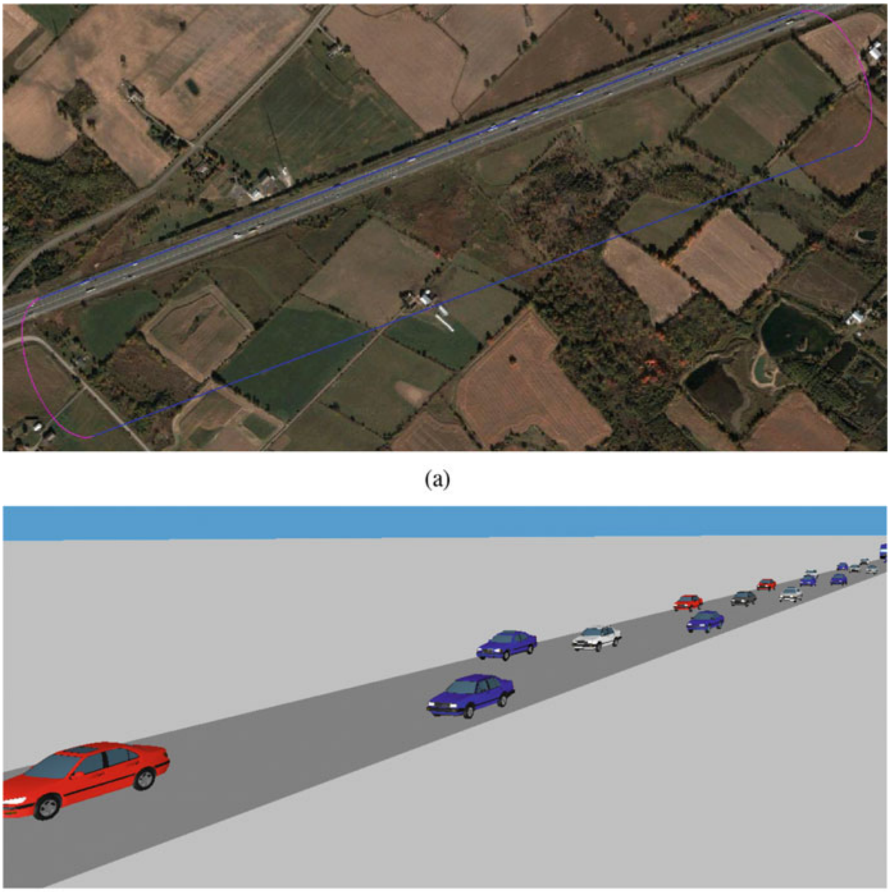
Fig. 5.6 Comparison of utilization of unreserved time slots in eCAH-MAC, CAH-MAC and ADHOC MAC with $\eta = 0.20$ [2]

To conduct the simulations, vehicles are injected to the road networks, with rate 2100, 2400 and 7200 vehicle per hour. After the injection period of 5 min, the number of vehicles in the network, denoted by $\aleph$, becomes 364, 496 and 622 respectively for the vehicle input rates. These vehicles are then allowed to move according to the corresponding traffic rules and road network parameters. To reduce any transient state effects, vehicle traces are not recorded for a warm-up period of 5 min after the injection period. As soon as warm-up period ends, i.e., after the first 10 min of simulation, vehicle traces are recorded at the interval of 0.1 s till the end of simulation. Thus, vehicle traces are recorded, in a plain text format, for the period of 5 min after the warm-up period. The vehicle traces consist of vehicle positions, i.e., x and y coordinates, and their speeds at a given time as shown in Fig. 5.8. The vehicle trace format in plain text format is then parsed and converted into a MATLAB readable format. Such vehicle traces are used to simulate the performance of eCAH-MAC, which is compared with that of CAH-MAC and ADHOC MAC. Figure 5.9 shows the vehicles in the simulated road network that is used to simulated the performance evaluation.

To realize the channel, autocorrelated Nakagami-m envelope sequences are generated following the procedure defined in [20]. First, a reference Rayleigh sequence is generated based on Jake model [8]. Correlation coefficient of the

Table 5.2 VISSIM simulation parameters [2]

Car-following (Wiedemann99)				Lane changing			Vehicle characteristics			
Parameter	Value	Parameter	Value	Parameter	Lane changer	Trailing vehicle	Parameter	Car	HGV	Bus
CC0	1.5 m	CC1	0.90 m	Maximum deceleration	$-4\ m/s^2$	$-3\ m/s^2$	Average length	4.44 m	11.54 m	11.54 m
CC2	4.0 m	CC3	−8.0	$-1\ m/s^2$ per distance	200 m	200 m	Width	1.5 m	2.5 m	2.5
CC4	−0.35	CC5	0.35	Accepted deceleration	$-1\ m/s^2$	$-0.50\ m/s^2$	% of the total # of vehicles	95%	15%	5%
CC6	11.44	CC7	$0.25\ m/s^2$	Simulation time: 5 min			Desire speed dist. (km/h)	U(90, 130)	U(85, 120)	U(85, 120)
CC8	$3.5\ m/s^2$	CC9	$1.50\ m/s^2$	Units in meter and second are denoted by m and s, respectively. Furthermore, default VISSIM parameters such as maximum/desired acceleration and deceleration functions for cars, HGVs and buses are used as described in [19]						



(a)

(b)

Fig. 5.7 Snap shots of the simulations showing: (**a**) Simulated ring of highway segment in blue; (**b**) Vehicles moving along the simulated road network

generated sequence is calculated as in (5.3) and (5.5), with slope and offset for the highway environment as in Table 5.3. Then, the Nakagami-*m* sequence is generated which follows the rank statistics of the reference Rayleigh sequence. Other simulation parameters are given in Table 5.1.

Figures 5.10 and 5.11 show the status of two-hop member nodes and time slots of the corresponding frame over various channel conditions. As the channel degrades (i.e., path-loss exponent value increases), a node fails to reserve or retain its time slot. Thus, a large number of nodes lose their time slots or fail to retain time slots, respectively, and become contending nodes. The increase in the number of contending nodes results in the larger number of unreserved time slots in the corresponding frame. At the beginning of the simulation, all nodes in the network

```
Vehicle Record

File:
Comment:
Date:
VISSIM:

t      : Simulation Time [s]
VehNr  : Number of the Vehicle
WorldX : World coordinate x (vehicle front end at the end of the
simulation step)
WorldY : World coordinate y (vehicle front end at the end of the
simulation step)
vMS    : Speed [m/s] at the end of the simulation step

      t;      VehNr;     WorldX;     WorldY;     vMS;
    0.1;          1; 1887.8547; 1038.8628;   26.64;
    0.2;          1; 1885.3621; 1037.9226;   26.64;
    0.2;          2;   97.9043;  340.1902;   26.02;
    0.3;          1; 1882.8694; 1036.9824;   26.64;
    0.3;          2;  100.3400;  341.1065;   26.03;
```

Fig. 5.8 Vehicle trace file from VISSIM

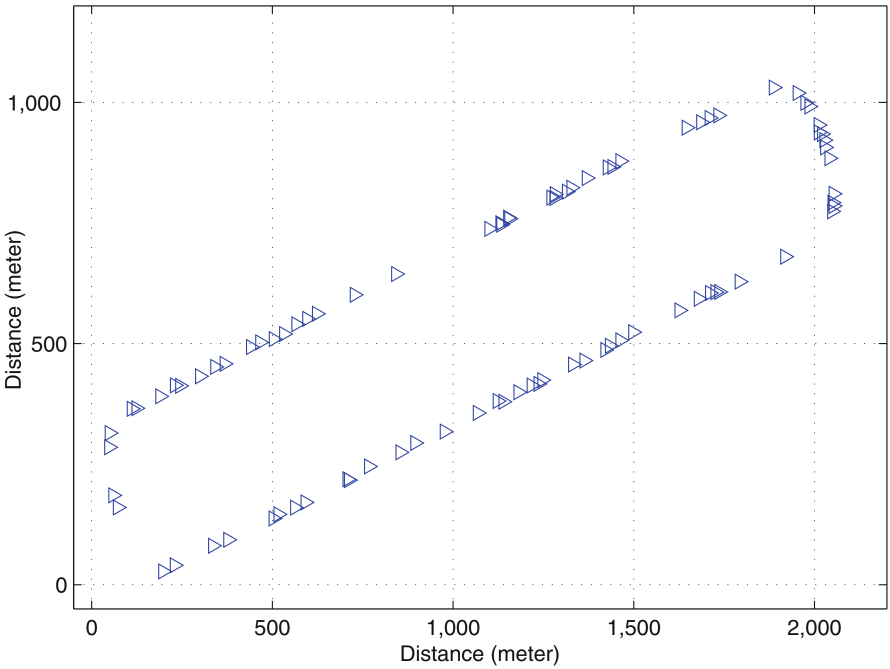


Fig. 5.9 A snap shot of the vehicles moving on the ring of highways during the MATLAB simulations

Table 5.3 Doppler spread parameters in different driving environments [13]

Parameter	Rural	Highway	Suburban
Offset (o)	0.500	0.200	11.20
Slope (θ)	0.420	0.414	0.428

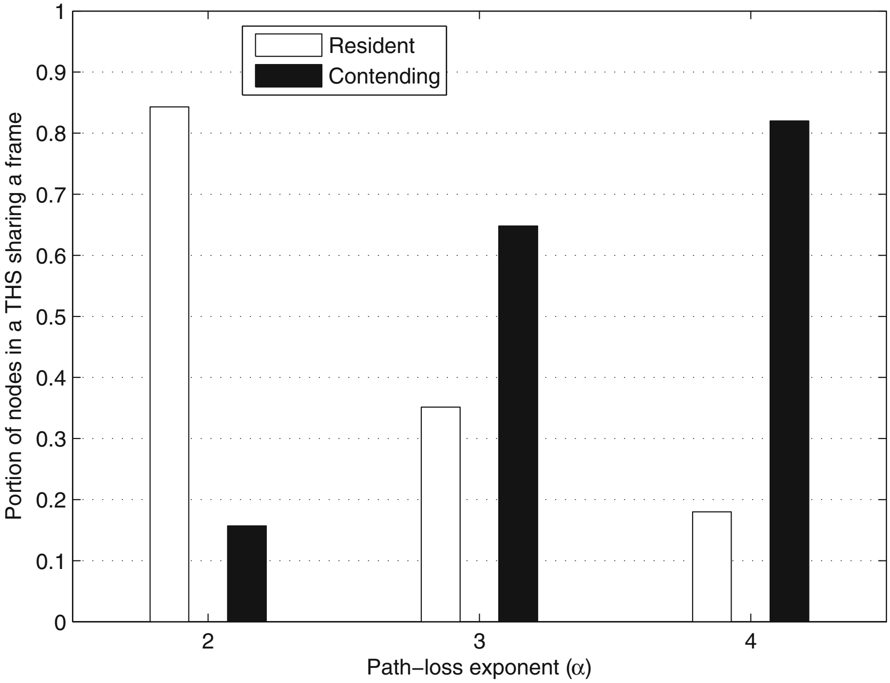


Fig. 5.10 Portion of the number of resident and contending nodes in a THS per frame with $\aleph = 622$ [2]

try to access the channel, which results in access collisions. As this scenario does not represent the normal networking condition, the following analysis are performed during the steady state. Figure 5.12 shows the frame-by-frame status of time slots during a steady state after the initial transitions. For a given networking scenario, the fractions of reserved (unreserved) time slot remains approximately constant at each time frame during the steady state.

Our objective is to study the effects of node cooperation on the operations of D-TDMA MAC. To evaluate the performance of eCAH-MAC, we study its efficiency in using an unreserved time slot selected for cooperative relay transmission. In doing so, we ignore unreserved time slots during which at least one of the following events occur:

1. Two or more contending nodes perform reservation attempts, and
2. Cooperative relay transmission is not scheduled for a failed direct transmission between an $s-d$ pair.

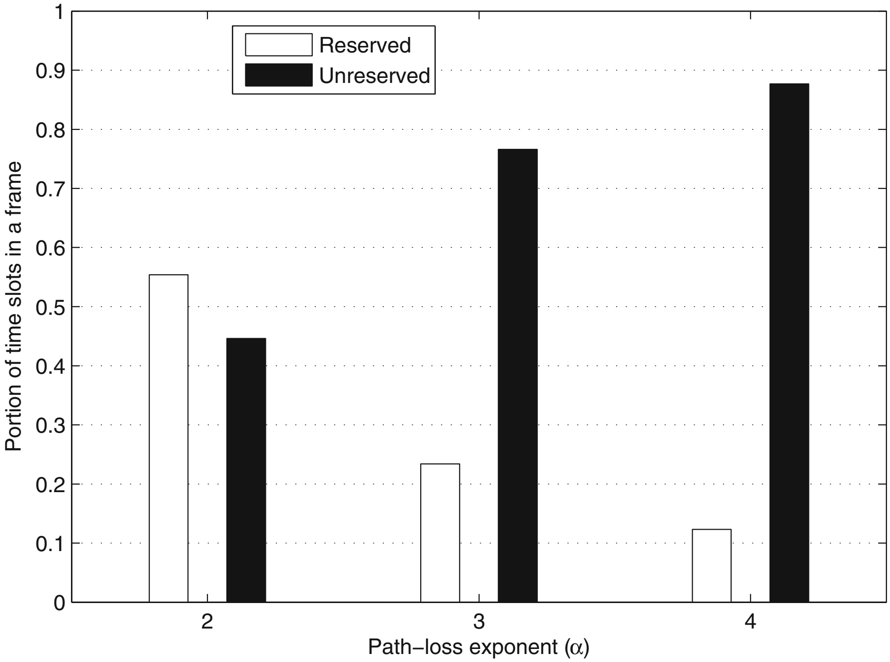


Fig. 5.11 Portion of reserved and unreserved time slots in a THS per frame with $\aleph = 622$ [2]

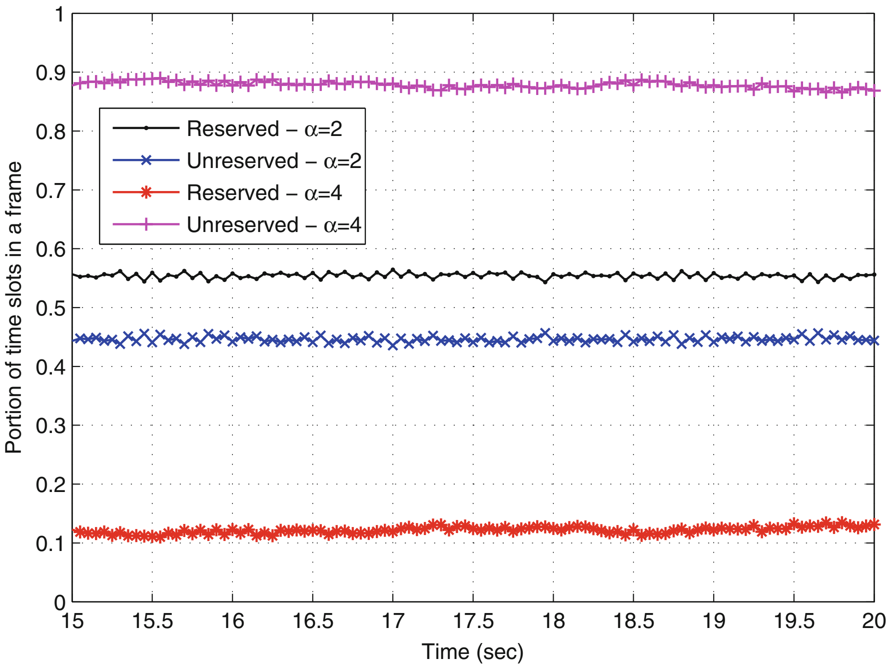


Fig. 5.12 Portion of reserved and unreserved time slots per frame per THS observed between consecutive frames in a steady state with $\aleph = 622$ [2]

When such events occur, time slot reservation attempts, if there are any, are not affected by node cooperation. On the other hand, if a cooperation is scheduled during an unreserved time slot, one of the following events occur

1. A helper node successfully relays the packet that it received from a source node to the target destination node, i.e., a successful cooperative relay transmission;
2. A helper node suffers from poor channel conditions and fails to relay the packet to the target destination node, i.e., a cooperative relay transmission fails due to poor channel condition;
3. Cooperative relay transmission fails due to transmission collision and/or gets suspended due to the reservation attempt from a contending node that is in one-hop transmission distance from the destination or helper nodes, i.e., cooperation collision occurs or cooperative relay transmission is suspended respectively.

Figures 5.13–5.15 show the probabilities at various networking conditions. With an increase in the number of nodes in the network (when $\aleph$ value increases) or as the channel quality degrades (when α value increases), the probability of successful cooperative relay transmission decreases. As a large number of nodes lose their

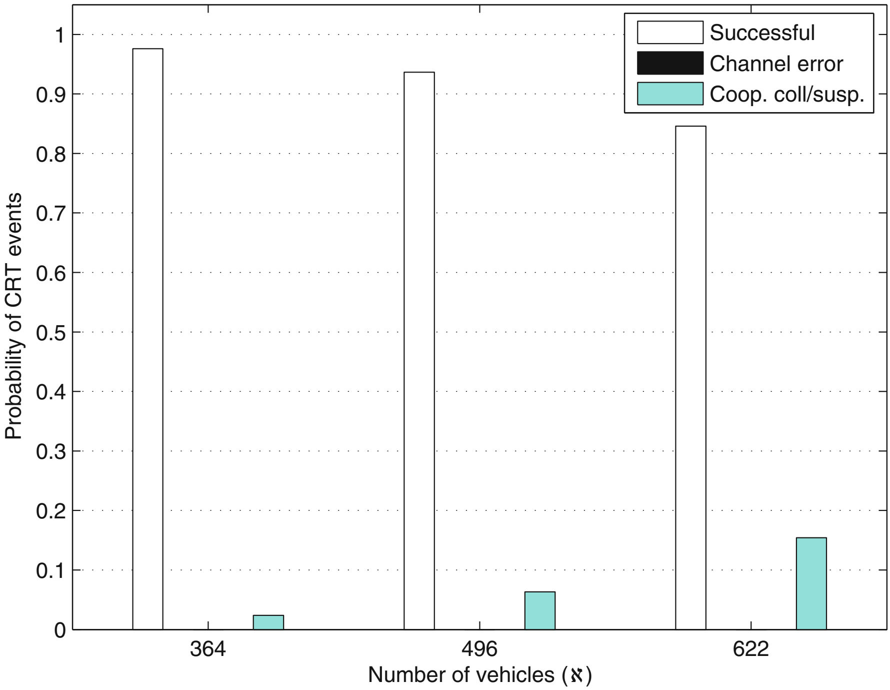


Fig. 5.13 Probability of events during cooperative relay transmission (CRT), such as successful CRT (Successful), failed CRT due to channel error (Channel error), and failed CRT due to cooperation collision in CAH-MAC or suspension of CRT to avoid cooperation collision in eCAH-MAC (Coop. coll/susp.), with $\alpha = 2$ [2]

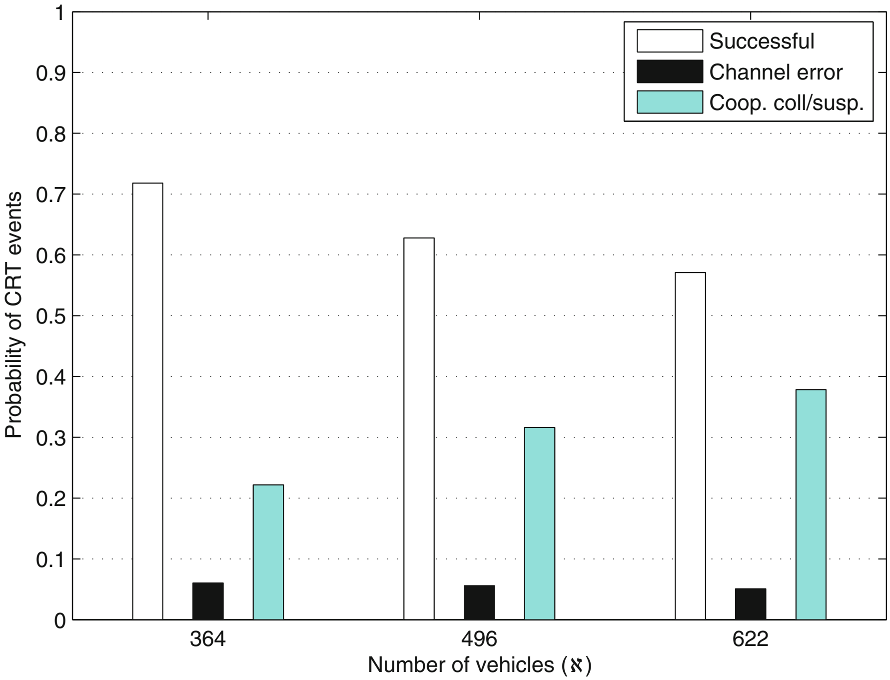


Fig. 5.14 Probability of events during cooperative relay transmission (CRT), such as successful CRT (Successful), failed CRT due to channel error (Channel error), and failed CRT due to cooperation collision in CAH-MAC or suspension of CRT to avoid cooperation collision in eCAH-MAC (Coop. coll/susp.), with $\alpha = 3$ [2]

time slots due to channel errors, an increase in α value increases the number of contending nodes. Moreover, for a given F value, an increase in the number of nodes in the network increases the number of contending nodes due to the lack of time slots. The larger the number of contending nodes, the higher the probability of reservation attempt(s) during an unreserved time slot. Thus, with an increase in the number of contending nodes, the number of time slot reservation attempts increases. Such a phenomenon forces helper and/or destination nodes to suspend the scheduled cooperative relay transmissions in eCAH-MAC or results in cooperation collisions in CAH-MAC, decreasing the probability of successful cooperative relay transmission. In CAH-MAC, cooperation collisions occur when either a helper node or a destination node and a contending node simultaneously perform cooperative relay transmission and time slot reservation. On the other hand, in eCAH-MAC, the cooperative relay transmission phase is suspended allowing the contending node to reserve the time slot.

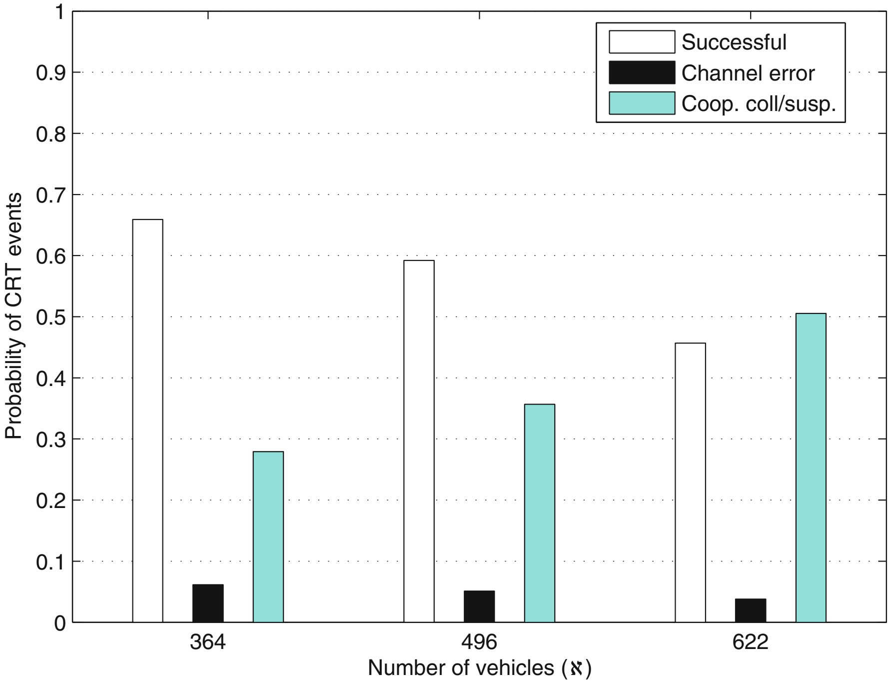


Fig. 5.15 Probability of events during cooperative relay transmission (CRT), such as successful CRT (Successful), failed CRT due to channel error (Channel error), and failed CRT due to cooperation collision in CAH-MAC or suspension of CRT to avoid cooperation collision in eCAH-MAC (Coop. coll/susp.), with $\alpha = 4$ [2]

Figures 5.16–5.18 show that the probability of successful utilization of an unreserved time slot in eCAH-MAC is higher than that in ADHOC MAC and CAH-MAC. The average number of OHS nodes increases with an increase in the number of nodes in the network ($\aleph$ value). Thus, with an increased $\aleph$ value, the probability of a contending node to successfully deliver its reservation packet to all of its OHS nodes in a poor channel condition decreases. Moreover, in CAH-MAC, the number of failures in time slot reservation attempts increases due to cooperation collisions from the ongoing cooperative relay transmissions, thus further wasting unreserved time slots. In eCAH-MAC, on the other hand, cooperative relay transmission is suspended allowing contending nodes to perform reservation attempts. Hence, eCAH-MAC uses an unreserved time slot more efficiently than that of CAH-MAC and ADHOC MAC.

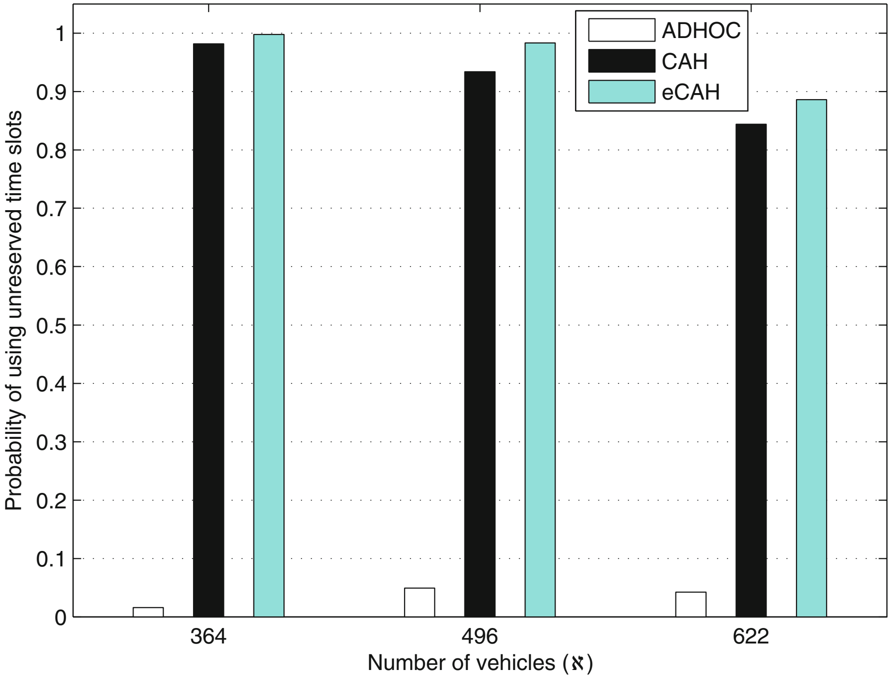


Fig. 5.16 Probability of successful usage of unreserved time slots in ADHOC MAC, CAH-MAC and eCAH-MAC with $\alpha = 2$ [2]

5.6 Summary

In this chapter, we present a collision avoidance scheme for the CAH-MAC protocol, referred to as enhanced Cooperative ADHOC MAC (eCAH-MAC). In the presence of networking environment dynamics, CAH-MAC suffers from cooperation collisions between cooperative relay transmissions and time slot reservations. In eCAH-MAC, the use of different packet types and black bursts to reserve a time slot and suspension and/or delay of cooperative relay transmission phase helps to avoid cooperation collisions. Consequently, unreserved time slots can be efficiently use to perform either cooperative relay transmissions or new time slot reservations. Through extensive simulation and mathematical analysis, we observe that in eCAH-MAC cooperation opportunities can be efficiently utilize without disrupting the normal operations of the distributed TDMA MAC.

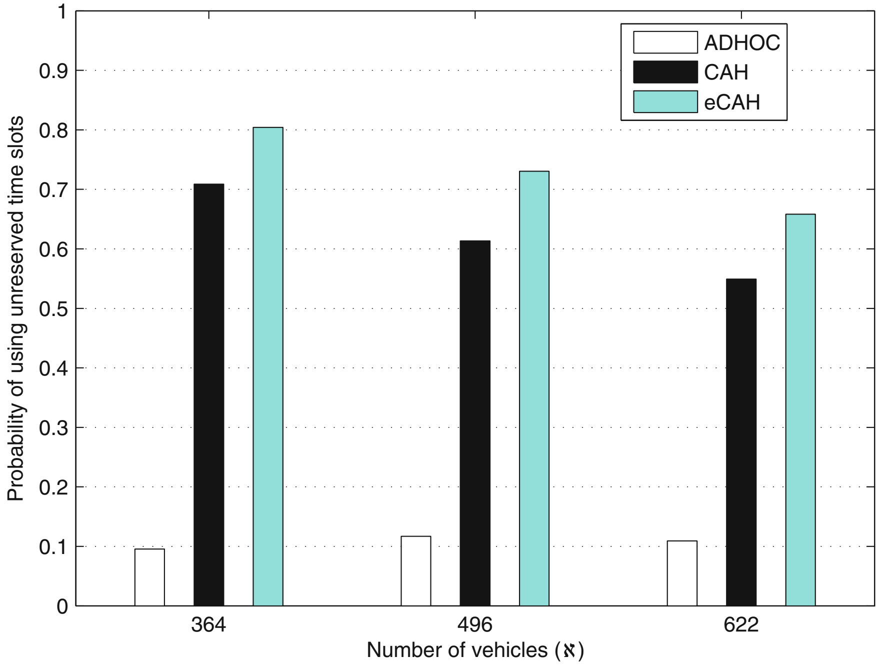


Fig. 5.17 Probability of successful usage of unreserved time slots in ADHOC MAC, CAH-MAC and eCAH-MAC with $\alpha = 3$ [2]

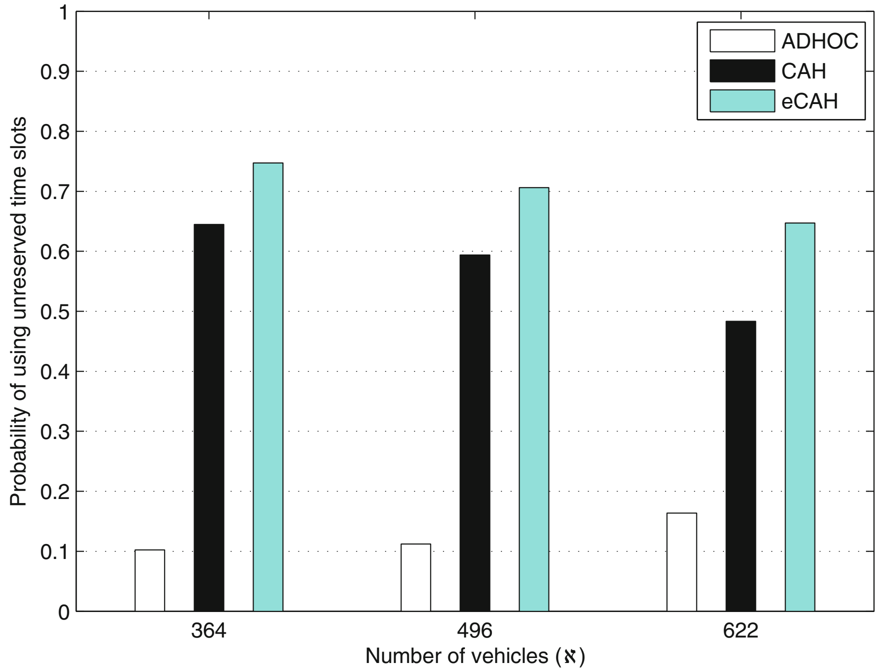


Fig. 5.18 Probability of successful usage of unreserved time slots in ADHOC MAC, CAH-MAC and eCAH-MAC with $\alpha = 4$ [2]

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Chapter 6
Cooperative Relay Broadcasting

In this chapter, we present node cooperation based makeup transmission framework for D-TDMA MAC in VANETs, referred to as *cooperative relay broadcasting* (CRB) [1]. In CRB, nodes with packet from a source node rebroadcast the packet before it expires, making it suitable for delay sensitive safety applications with strict QoS requirements. As discussed in Sect. 1.1, delay sensitive safety applications demand an efficient, quick, and reliable broadcast service. However, the existing D-TDMA MAC protocols lack a makeup strategy to tackle a transmission failure due to the wireless channel impairments in VANETs. The lack of a makeup strategy in D-TDMA MAC results in the following problems in broadcast services:

1. To determine its broadcast status (successful or fail broadcast), a node must analyze FIs from all of its one-hop neighboring nodes, which takes the duration of a time frame. Thus, to decide whether to rebroadcast a safety packet or not, a source node waits for the duration of a time frame. Such a wait may result in an undesirable packet transmission delay, in case of failed broadcast, and further result in packet dropping if the packet expiry time limit is exceeded;
2. If a source node fails to broadcast a safety packet, it must wait for its own time slot in the next frame to rebroadcast the packet even if the channel is idle during unreserved time slots. On the other hand, the safety packet can be rebroadcast (before the source node's next transmission) during unreserved time slots, which reduces the packet delay;
3. If a source node fails to broadcast a safety packet, rebroadcasting of the packet from the source node may not be helpful as the propagation channel likely remain the same. For example, the presence of a large obstacle (such as a large vehicle) in between two vehicles can lead to frequent link breakage and failure in transmission even after multiple attempts due to the obstruction in line-of-sight [2].

As a result, the D-TDMA MAC may not be able to achieve the required QoS if the source node rebroadcasts the packet. Hence, it is necessary for the D-TDMA MAC

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to have a makeup strategy that provides a quick and reliable one-hop broadcast service specifically to satisfy the strict QoS requirements of the delay sensitive safety applications in VANETs.

Node cooperation schemes, such as CAH-MAC and eCAH-MAC, as discussed in Chaps. 4 and 5 respectively, deploy a makeup strategy for a point-to-point communication in D-TDMA MAC. However, to the best of our knowledge, a makeup strategy for broadcast service in D-TDMA based MAC is not yet available. Furthermore, the existing makeup strategies for broadcast service in wireless networks, as discussed in Sect. 2.2.3, cannot be directly applied to D-TDMA. Motivated from the lack of a suitable makeup strategy for D-TDMA MAC, in this chapter, we focus on developing a framework for makeup transmission in D-TDMA based broadcast service in VANETs, which supports safety applications demanding a quick and reliable broadcast service. The neighboring nodes with a valid packet (safety packet broadcast from a source node) cooperate with the nodes without the packet with an object to maximize the number of nodes with the packet before it expires. The key contributions of this chapter are as follows:

1. We propose a framework to perform cooperative relay broadcasting (CRB) in D-TDMA. The CRB is performed during unreserved time slots in order to make up for the transmission failures during the source node's time slot. Furthermore, it is performed by nodes, referred to as the best helper nodes, which have the packet from source node and is in good channel conditions with the nodes which failed to receive the packet transmitted the source node. The main objective of the proposed CRB framework is to maximize the number of nodes which successfully receive a packet before it expires.
2. We formulate an optimization problem to select the best helper nodes to perform CRB. The formulated optimization problem required an accurate channel state information (CSI) and provides an upper bound of the CRB performance in maximizing the number of nodes with successful packet reception. The obtained upper bound can be set as a benchmark for the performance evaluation of other helper selection schemes.
3. We propose a channel prediction scheme that can be used to find the best helper node to perform CRB. The proposed channel prediction scheme determines the channel quality and node cardinality to perform CRB using the local information that are transmitted during the normal operation of D-TDMA.

Next, the system model and necessary assumptions concerning the transmission channel are discussed.

6.1 System Overview

We consider a network where all nodes have already reserved their time slots. The frame size is large such that there are no contending nodes seeking for time slots and all the nodes in the network have already reserved their time slots. Furthermore, nodes share their positions and velocities periodically from the application layer of the protocol stack as some safety applications require such information for their normal operations [3]. Thus, nodes are aware of positions and velocities of their OHS nodes.

6.1.1 Two-State Markov Channel

Let the quality of the wireless propagation channel between a pair of transmitting and receiving nodes be in either good or bad state, i.e, the channel can be in either *good* or *bad* state. The channel is considered to be in the *good* state, if the received power at the receiving node, which is at distance r meters from the transmitting node, is equal to or greater than a threshold value, i.e., $\gamma_r \geq \gamma_{th}$; otherwise, the channel is considered to be in the *bad* state. The state of the channel remains unchanged during the interval that is equal to the duration of a time slot, i.e., the strength of the received power remains same during the entire duration of a time slot. In the next time slot, the channel either remains in the same state as in the current time slot or alters to the other state. Let random process $\{\mathcal{M}_i\}$ denotes the channel state during time slots $i = 1, 2, 3, \ldots$. Thus, $\mathcal{M}_i$ can be represented by a two-state first-order Markov chain with transition probabilities P_{gg}, $1 - P_{gg}$, $1 - P_{bb}$ and P_{bb}, as shown in Fig. 6.1. Furthermore, the transition probability, P_{gg}, can be written as

$$\begin{aligned} P_{gg} &= \Pr\{\mathcal{M}_{i+1} = good|\mathcal{M}_i = good\} \\ &= \frac{\int_{\gamma_{th}}^{\infty} \int_{\gamma_{th}}^{\infty} f_{\gamma_1,\gamma_2}(x_1, x_2) dx_1 dx_2}{1 - F_{\gamma_1}(\gamma_{th})} \\ &= \frac{1 - F_{\gamma_{r_i}}(\gamma_{th}) - F_{\gamma_{r_{i+1}}}(\gamma_{th}) + F_{\gamma_{r,2}}(\gamma_{th}, \gamma_{th})}{1 - F_{\gamma_{r_i}}(\gamma_{th})} \end{aligned} \tag{6.1}$$

where $F_{\gamma_r,2}(.,.)$ is the bivariate cumulative distribution function (cdf) and $F_{\gamma_{r_i}}(.)$ is the cdf of the amplitude of received signals at the time slot i. Similarly, the transition probability, P_{bb}, can be written as

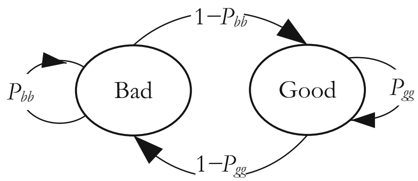

Fig. 6.1 Two-state Markov chain channel

$$P_{bb} = \Pr\{\mathcal{M}_{i+1} = bad | \mathcal{M}_i = bad\}$$
$$= \frac{\int_0^{\gamma_{th}} \int_0^{\gamma_{th}} f_{\gamma_1,\gamma_2}(x_1, x_2) dx_1 dx_2}{F_\gamma(\gamma_{th})}$$
$$= \frac{F_{\gamma,2}(\gamma_{th}, \gamma_{th})}{F_{\gamma_{r_i}}(\gamma_{th})}. \tag{6.2}$$

Consequently, the steady state probability of the channel to be in the *good* state during a time slot, denoted as π_g, is given by

$$\pi_g = \frac{1 - P_{bb}}{2 - P_{gg} - P_{bb}}. \tag{6.3}$$

Transition probabilities in (6.1) and (6.2) depend on the cdf and bivariate cdf of the fading statistics, i.e., $F_{\gamma_r}(.)$ and $F_{\gamma_r,2}(.,.)$ respectively. In the system, a generalized Nakagami-*m* channel with correlated amplitudes is considered. The cdf of the received power for the Nakagami-*m* channel is given by

$$F_{\gamma_r}(x) = 1 - \frac{\Gamma(m, m\frac{x}{\bar{\gamma}_r})}{\Gamma(m)} \tag{6.4}$$

where $\Gamma(\cdot,\cdot)$ is the upper incomplete Gamma function. Given two non-negative correlated Nakagami-*m* random variables, say X_1 and X_2, the bivariate pdf is given by Nakagami [4]

$$f_{X,2}(x_1, x_2; m, \varrho) = \frac{4m^{m+1}(x_1x_2)^m}{\mu_1\mu_2(1-\varrho)(\sqrt{\mu_1\mu_2\varrho})^{m-1}\Gamma(m)}$$
$$\times \exp\left\{-\frac{m}{1-\varrho}\left(\frac{x_1^2}{\mu_1} + \frac{x_2^2}{\mu_2}\right)\right\}$$
$$\times I_{m-1}\left(\frac{2m\sqrt{\varrho}}{\sqrt{\mu_1\mu_1}(1-\varrho)}x_1x_2\right) \tag{6.5}$$

where

- $f_{X,2}(\cdot,\cdot)$ is the bivariate pdf,
- $\mu_i = E(X_i^2)$, $i = \{1, 2\}$,
- $I_v(\cdot)$ is the vth order modified Bessel function of the first kind, and
- ϱ is the correlation coefficient.

For integer *m* values, the corresponding cdf is given by (6.6) [5], where

- $F_{X,2}(\cdot,\cdot)$ is the bivariate cdf,
- $\Phi_3(\cdot,\cdot;\cdot,\cdot)$ is the confluent hypergeometric function, which can be approximated as

$$
\begin{aligned}
F_{X,2}(x_1, x_2; m, \varrho) &= 1 - \sum_{k=0}^{m-1} \left[\exp\left(-\frac{mx_2^2}{\mu_2}\right) \left(\frac{mx_2^2}{\mu_2}\right)^k \frac{1}{k!} \right. \\
&+ \left(\frac{mx_1^2}{\mu_1}\right)^k \frac{1}{k!} (1-\varrho)^{-k} \exp\left\{ -\frac{m}{1-\varrho} \left(\frac{x_1^2}{\mu_1} + \frac{x_2^2}{\mu_2}\right) \right\} \\
&\times \left\{ \left(\frac{mx_2^2}{\mu_2}\right)^k \frac{1}{k!} \right. \\
&\times \Phi_3\left(1, k+1; \frac{x_2^2}{\mu_2} \frac{m}{(1-\varrho)} \varrho \left(\frac{x_1}{\sqrt{\mu_1}} \frac{x_2}{\sqrt{\mu_2}} \frac{m}{(1-\varrho)}\right)^2\right) \\
&- \sum_{i=1}^{m-k} \left(\frac{mx_2^2}{\mu_2}\right)^{k+i-1} \frac{1}{(k+i-1)!} \\
&\times \left. \left. \Phi_3\left(i, k+i; \frac{x_2^2}{\mu_2} \frac{m\varrho}{(1-\varrho)}, \varrho \left(\frac{x_1}{\sqrt{\mu_1}} \frac{x_2}{\sqrt{\mu_2}} \frac{m}{(1-\varrho)}\right)^2\right) \right\} \right]
\end{aligned}
\tag{6.6}
$$

$$
\Phi_3(j, e; \psi, z) \approx \sum_{k=0}^{2m-1} \frac{(j)_k \Gamma(e)}{k!} \frac{\psi^k}{z^{(e+k-1)/2}} I_{e+k-1}(2\sqrt{z}), \tag{6.7}
$$

- $(j)_k$ is the Pochhammer symbol [6], which is defined as

$$
\begin{aligned}
(j)_k &= j(j+1)\cdots(j+k-1) \\
(j)_0 &= 1 \text{ and } k = 1, 2, \cdots .
\end{aligned}
\tag{6.8}
$$

From (6.4) and (6.6), the transition probabilities in (6.1) and (6.2) can be calculated and used to calculate the steady state probability in (6.3). The transition probabilities depend on the correlation coefficient of a received signal at two different time slots, which is given in (5.3).

6.2 Node Cooperation for Broadcast Service in D-TDMA MAC

This section presents the proposed CRB procedure to realize a node cooperation based makeup strategy for D-TDMA based MAC protocols. Such a makeup transmission is to ensure that a safety message must reach at least 99% of the target destination nodes within 100 ms, to satisfy high communication reliability and strict delay requirements. The strict service requirements in the broadcast service demand a distributed and efficient cooperation decisions, such as in selection of time slot and helper node, to perform CRB. To make such cooperation decisions, information including node cardinality and channel quality information is required, which adds further challenges in developing the cooperative broadcast scheme. In the following, we discuss the cooperation decisions as a part of the proposed CRB framework in D-TDMA MAC to provide a reliable broadcast service in VANETs.

Consider nodes in an area of interest, which include a source node, denoted as S, and nodes in its one-hop transmission distance. Node S broadcasts a packet, referred to as tagged packet, targeting its one-hop neighboring nodes or nodes in the area of interest. Due to channel impairments, some nodes fail to receive the tagged packet. Let $\mathcal{H}$ and $\mathcal{D}$ denote the sets of nodes that have and do not have the tagged packet, respectively. Nodes in sets $\mathcal{H}$ and $\mathcal{D}$ are referred to as potential helper nodes (PHNs) and potential destination nodes (PDNs), respectively. In CRB, PHNs cooperate to rebroadcast the tagged packet to PDNs. A safety message is not relevant and expires after its expiry time, after which the information in the message is not valid. Consequently, each tagged packet, in which a safety message is embedded, has an expiry time, and it is not necessary to broadcast or rebroadcast the tagged packet after its expiry time. In CRB, PHNs do not cooperate to rebroadcast the tagged packet after the packet expires. For presentation clarity, here we consider that a packet expires after the duration of one time frame from the start of source node's time slot, i.e., start of the packet transmission.

To meet the strict QoS requirement, the objective of CRB is be to maximize the number of nodes which successfully receive the tagged packet before the packet expires. Our strategy is to use each available unreserved time slot for CRB during which only one PHN performs CRB to serve PDNs that are in its one-hop transmission distance and are in a good channel condition. The CRB operations is detailed in the following:

1. Source node S broadcasts a packet with safety message during its time slot, targeting all of one-hop neighboring nodes, denoted by set $\mathcal{O}_S$. Without the loss of generality, we consider that the source node owns the first time slot.
2. Among all the one-hop neighboring nodes of S in $\mathcal{O}_S$, some nodes receive the packet and the remaining others fail to receive it; as discussed previously, the ones which receive the packet are in set $\mathcal{H} \subseteq \mathcal{O}_S$ and others are in $\mathcal{D} \subseteq \mathcal{O}_S$.
3. As soon as the source node transmits the packet, PHNs in set $\mathcal{H}$ wait for the next immediate unreserved time slot to perform CRB of the packet to serve the PDNs in their corresponding OHSs. While waiting an unreserved time slot, a PHN evaluates itself and performs CRB only if it evaluates itself as the best potential helper nodes among all PHNs in its one-hop neighborhood. Procedures to perform the self-evaluation and evaluation of one-hop neighboring nodes are to be discussed.
4. During the next unreserved time slot, the best helper node, say $z \in \mathcal{H}$, performs CRB targeting all the PDNs in its one-hop distance.
5. On receiving the tagged packet successfully from the best helper nodes, a PDN may become a PHN, and sets $\mathcal{D}$ and $\mathcal{H}$ are updated accordingly.
6. Operations from step 4 are repeated, during the next unreserved time slot until the time frame finishes.

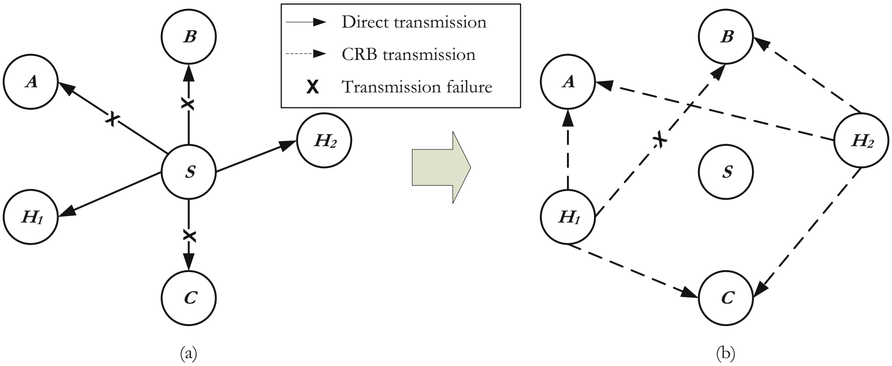

Fig. 6.2 Illustration of the selection of the best helper to perform CRB. (**a**) Source node S broadcasts a packet to its one-hop neighbors and fails to deliver the packet to nodes A, B and C; (**b**) Node H_2 is able to serve the larger number of nodes (nodes A, B and C) as compared to node H_1 (able serve nodes A and C only) [1]

The cooperation decisions should be made to improve the transmission reliability, such that the broadcast (tagged) packet can spread among all the nodes in the area of interest before it expires. Thus, the goals are to

1. maximize the number of nodes in the area of interest which successfully receive the packet before it expires, and
2. minimize the transmission delay.

Figure 6.2 shows an example of the selection of a best helper node, where node H_2 is selected as the best helper nodes over node H_1 if node B will not be served by node H_1 during CRB. To achieve the goals, CRB is performed during all the available unreserved time slots. Furthermore, the best helper node in each unreserved time slot is selected based on information such as node cardinality, channel condition and time slot usage, without imposing extra overhead on the D-TDMA MAC.

In the following, we present two helper selection schemes for CRB of a tagged packet. First, an optimal helper selection scheme is presented under the assumption that each node is aware of accurate CSI to its one-hop neighboring nodes. Such an optimal helper selection scheme provides the maximum achievable performance gain over non-cooperative broadcasting and can be used to set a benchmark for performance evaluation. As the accurate knowledge of CSI requires a high overhead, the proposed optimal helper selection is not practical to implement in VANETs scenario with dynamic networking conditions. Accordingly, a simple helper selection scheme is presented which is based on local information exchanged during normal (non-cooperative) transmissions and shown to provide a significant performance gain over the existing D-TDMA MAC.

6.3 Optimal Helper Selection with Accurate Channel Information

In order to determine the best helper node to perform CRB, we formulate an optimization problem that requires a precise CSI among nodes in the area of interest. The optimization problem aims to maximize the number of nodes which successfully receive the tagged packet during the CRB in a given unreserved time slot. In the following, we describe the variables of the optimization problem and their relationship with sets $\mathcal{D}$ and $\mathcal{H}$. Based on such variables, the optimization problem is formulated to select the best helper node.

Define set $\mathcal{K}$ as

$$\mathcal{K} = \{k_{xy} \mid k_{xy} = \{0, 1\}, x \in \mathcal{D}, y \in \mathcal{H}\} \tag{6.9}$$

where k_{xy} is a binary indicator variable, equal to 1 if node x in $\mathcal{D}$ receives the tagged packet from node y in $\mathcal{H}$, and 0 otherwise.

Similarly, define set $\mathcal{Q}$ as

$$\mathcal{Q} = \{q_y \mid q_y = \{0, 1\}, y \in \mathcal{H}\} \tag{6.10}$$

where q_y is a binary indicator variable, equal to 1 if node y in $\mathcal{H}$ is selected to relay the packet, and 0 otherwise.

Let $\mathcal{V}$ be the set of transmission results which depend on channel quality, defined as

$$\mathcal{V} = \{v_{yx} \mid v_{yx} = \{0, 1\}, x, y \in \{\mathcal{O}_s \cup s\}\} \tag{6.11}$$

where v_{yx} is a binary indicator variable, equal to 1 if the transmission from node y to node x is successful, and 0 otherwise. Here, $\mathcal{V}$ is known to all the nodes in the area of interest.

For given set $\mathcal{V}$, we aim to find a PHN in set $\mathcal{H}$ to relay the packet in a given unreserved time slot, such that the number of PDNs in $\mathcal{D}$ receiving the packet is maximized before it expires. Sets $\mathcal{D}$ and $\mathcal{H}$ can be determined with the knowledge of set $\mathcal{V}$ and FIs exchanged among one-hop neighboring nodes. The helper selection is performed only if there is at least one PHN and one PDN, i.e., if $|\mathcal{H}| > 0$ and $|\mathcal{D}| > 0$. Thus, the objective of the helper selection scheme is to maximize $\sum_{x\in\mathcal{D}} \sum_{y\in\mathcal{H}} k_{xy}$. Furthermore, the constraints on $\mathcal{K}$ and $\mathcal{Q}$ are as follows:

1. The CRB opportunity during an unreserved time slot should not be wasted. Thus, to avoid transmission collisions, there should not be more than one PHN to relay the packet during an unreserved time slot. However, there must be at least one node in set $\mathcal{H}$ to relay the tagged packet;
2. A PDN should only receive the packet from a single PHN during an unreserved time slot. Transmission collision occurs if two or more PHNs relay the packet during the unreserved time slot. Such transmission collisions result in transmission failures and hence waste the CRB opportunities;

3. If a PHN, say node y in $\mathcal{H}$, relays the packet, a PDN, say node x in $\mathcal{D}$, receives the tagged packet only if $v_{yx} = 1$.

Based on the aforementioned, an optimization problem can be formulated for the helper selection and is given by

$$\underset{k_{xy},q_y}{\text{maximize}} \sum_{x\in\mathcal{D}} \sum_{y\in\mathcal{H}} k_{xy} \tag{6.12a}$$

$$\text{Subject to: } \sum_{y\in\mathcal{H}} q_y = 1, \tag{6.12b}$$

$$\sum_{y\in\mathcal{H}} k_{xy} \leq 1, \qquad \forall x \in \mathcal{D}, \tag{6.12c}$$

$$k_{xy} - v_{yx}q_y = 0, \qquad \forall y \in \mathcal{H}, \forall x \in \mathcal{D}, \tag{6.12d}$$

$$k_{xy}, q_y = \{0, 1\}, \qquad \forall y \in \mathcal{H}, \forall x \in \mathcal{D}. \tag{6.12e}$$

The objective function in (6.12a) and constraints in (6.12b)–(6.12d) are linear functions of the binary indicator variables k_{xy} and q_y. Hence, the optimization problem in (6.12) can be solved by using any binary integer linear programming technique. The optimal helper or the best potential helper node, denoted as y', is the one among all the nodes in set $\mathcal{H}$ and has $q_{y'} = 1$ from (6.12). Similarly, the set of optimum PDNs, denoted as $\mathcal{D}'$, is a subset of $\mathcal{D}$ and is given by

$$\mathcal{D}' = \{x \mid x \in \mathcal{D}, v_{y'x} = 1\}. \tag{6.13}$$

When node y' performs CRB of the tagged packet, nodes in set $\mathcal{D}'$ receive the packet and become PHNs. Accordingly, sets $\mathcal{D}$ and $\mathcal{H}$ are updated as

$$\mathcal{D} = \mathcal{D} - \mathcal{D}', \qquad \mathcal{H} = \mathcal{H} \cup \mathcal{D}'. \tag{6.14}$$

6.4 Helper Selection with Channel Prediction

The previously discussed optimal helper selection scheme requires the accurate knowledge of CSI, which is not practical to implement, especially in the highly dynamic vehicular networking environment. Thus, a more realistic helper selection scheme is required, which is presented in this section. To realize a practical helper selection scheme, each node in set $\mathcal{H}$ performs helper evaluation based on its local information, namely the number of OHS nodes, time slot usage information, and link quality. Node cardinality and time slot ownership information can be extracted from FIs exchanged among one-hop neighboring nodes, while the quality of the radio propagation channel is estimated (will be discussed).

A PHN, say $z \in \mathcal{H}$, evaluates itself as the best helper node to perform the CRB of the tagged packet if it can successfully deliver the packet to a largest number of nodes in set $\mathcal{D}$. While determining the number of neighboring nodes in set $\mathcal{D}$, node z counts its one-hop neighbors that have already announced transmission failures during their time slots, referred to as reported failed nodes. Thus, the time slots of reported failed nodes are earlier than the selected unreserved time slot in the current frame. Further, the PHN estimates the link quality to predict the transmission status of the remaining one-hop nodes that have not yet accessed the channel to send their FIs, referred to as predicted failed nodes (will be discussed). Let $\mathcal{R}_z^f$ and $\mathcal{P}_z^f$ denote the sets of reported and predicted fail nodes, respectively, from the perspective of node z. Hence, $\mathcal{O}_z^f \stackrel{\Delta}{=} \mathcal{R}_z^f \cup \mathcal{P}_z^f$ denotes the set of one-hop neighboring nodes of PHN z which failed to receive the tagged packet. In addition, node z determines the set of reported (predicted) successful nodes, denoted as $\mathcal{R}_z^s$ ($\mathcal{P}_z^s$), which have already (have not yet) announced the successful reception of the tagged packet. Thus, $\mathcal{O}_z^s \stackrel{\Delta}{=} \mathcal{R}_z^s \cup \mathcal{P}_z^s$ denotes the set of one-hop neighboring nodes of PHN z which successfully received the tagged packet. Note that node z determines sets $\mathcal{R}_z^s$ and $\mathcal{R}_z^f$ based on FIs that it receives after the source node's time slot. On the other hand, sets $\mathcal{P}_z^s$ and $\mathcal{P}_z^f$ are predicted by node z based on the estimation of the corresponding link qualities. To avoid redundant CRBs, node z accounts for CRBs that are already performed in its one-hop neighborhood for a given tagged packet, while determining the predicted sets ($\mathcal{P}_z^s$ and $\mathcal{P}_z^f$). To do so, node z excludes nodes in $\mathcal{P}_z^f$ which may have received the packet during the previous CRBs and include them in set $\mathcal{P}_z^s$. In the following, we discuss how to determine the sets of predicted failed and successful nodes based on channel prediction.

6.4.1 *Prediction of Failed and Successful Nodes*

The quality of the radio propagation channel (or channel quality) between an $s-d$ pair is predicted to decide whether or not a transmitted packet was or will be successfully delivered to the destination node. Such a prediction of the channel quality is based on a calculated average probability of successful communication, which is equivalent to the steady state probability of the channel to be in the *good* state during a time slot of a two-state first-order Markov channel model, as discussed in Sect. 6.1. Thus, π_g is the calculated average probability of successful communication and calculated as in (6.3). The channel quality is predicted to be in a good condition, if the calculated probability value is greater or equal to a threshold value, denoted as π_{th}. Thus, the channel quality during the entire duration of a time slot is predicted to be in either good or bad condition. The channel is in a good condition if $\pi_g \geq \pi_{th}$ and in a poor condition otherwise. Nodes use the positions and velocities of their one-hop neighboring nodes to determine the probability of

Algorithm 1 Determination of the sets of predicted failed and successful nodes by PHN z [1]

Input: S, $\mathcal{O}_z^r$, $\mathcal{O}_z$, Π_z, π_{th} and $\mathcal{O}_z^{crb}$

Initialization: $\mathcal{O}_z^p = \mathcal{O}_z - \mathcal{O}_z^r$, $\mathcal{P}_z^f = \emptyset$, $\mathcal{P}_z^s = \emptyset$, and a dummy set $\mathcal{G} = \emptyset$;

for $x \in \mathcal{O}_z^p$ **do**

if $\pi_{gz}^{sx} < \pi_{th}$ **then**

$\mathcal{P}_z^f \leftarrow \mathcal{P}_z^f \cup x$;

else

$\mathcal{P}_z^s \leftarrow \mathcal{P}_z^s \cup x$;

end if

end for

$\mathcal{G} = \mathcal{P}_z^f$

for $y \in \{\mathcal{O}_z^{crb} \cap \mathcal{O}_z\}$ **do**

for $x \in \mathcal{P}_z^f$ **do**

if $\pi_{gz}^{yx} \geq \pi_{th}$ **then**

$\mathcal{P}_z^s \leftarrow \mathcal{P}_z^s \cup x$;

$\mathcal{G} \leftarrow \mathcal{G} - x$;

break;

end if

end for

end for

$\mathcal{P}_z^f = \mathcal{G}$;

Output: $\mathcal{P}_z^f$ and $\mathcal{P}_z^s$

finding a channel in the *good* state. For instance, node z predicts the channel between transmitting node x and receive node y, based on the calculated probability of finding the channel in the *good* state, denoted as π_{gz}^{xy}. Set $\Pi_z = \{\pi_{gz}^{xy}\}$ is then used to determine the sets of predicted failed and successful nodes from the perspective of node z. The procedure to determine the predicted sets is given in Algorithm 1 for node z, where

1. $\mathcal{O}_z^{crb}$ denotes the set of PHNs which are in one-hop transmission distance from node z and have already performed CRB before the selected unreserved time slot;
2. $\mathcal{O}_z^r \overset{\Delta}{=} \mathcal{R}_z^s \cup \mathcal{R}_z^f$ denotes the set of one-hop neighboring nodes of node z that have already announced their transmission status from the source node.

6.4.2 Cooperation Decisions

Node $z \in \mathcal{H}$ first determines sets $\mathcal{O}_z^s$ and $\mathcal{O}_z^f$. Then, it evaluates and compares itself with the other successful nodes (both predicted and reported) in set $\mathcal{O}_z^s$. To evaluate itself, it determines a set of failed nodes to which it can successfully relay the tagged packet in a given unreserved time slot, denoted as $\mathcal{A}_{zz} \subseteq \mathcal{O}_z^f$. Then, it determines

Algorithm 2 Determination of the sets of failed nodes that are in a good channel condition with PHN z and its one-hop successful nodes

Input: $z, \mathcal{O}_z^f, \mathcal{O}_z^s, \Pi_z$ and π_{th}
Initialization: $\mathcal{A}_{zz} = \emptyset$ and $\mathcal{A}_{zy} = \emptyset$, $\forall y \in \mathcal{O}_z^s$;
for $x \in \mathcal{O}_z^f$ **do**
  if $\pi_{gz}^{zx} \geq \pi_{th}$ **then**
    $\mathcal{A}_{zz} \leftarrow \mathcal{A}_{zz} \cup x$;
  end if
  for $y \in \mathcal{O}_z^s$ **do**
    if $\pi_{gz}^{yx} \geq \pi_{th}$ **then**
      $\mathcal{A}_{zy} \leftarrow \mathcal{A}_{zy} \cup x$;
    end if
  end for
end for
Output: $\mathcal{A}_{zz}$ and $\mathcal{A}_{zy}$

sets $\mathcal{A}_{zy} \subseteq \mathcal{O}_z^f$ for node y, $\forall y \in \mathcal{O}_z^s$, as given in Algorithm 2.[1] Based on $\mathcal{A}_{zz}$ and $\mathcal{A}_{zy}$, $\forall y \in \mathcal{O}_z^s$, node z performs CRB in the selected unreserved time slot, if all of the following conditions are satisfied:

1. There is at least one failed node, either predicted or reported, which can successfully receive the tagged packet through CRB from z, i.e., $|\mathcal{A}_{zz}| > 0$;
2. Node z can relay the packet to a largest number of failed nodes (both predicted and reported combined) among all nodes in $\mathcal{O}_z^s$, i.e., $|\mathcal{A}_{zz}| > |\mathcal{A}_{zy}|$ for any node y in $\mathcal{O}_z^s$;
3. When there is one or more nodes that can relay to the same maximum number of failed nodes, node IDs will be used to make the cooperation decision. If $|\mathcal{A}_{zz}| = |\mathcal{A}_{zy}|$, $\forall y \in \mathcal{O}_z^s$, node z relays the packet instead of node y if node z's ID is less than the ID of node y.

6.4.3 *Re-broadcasting of Tagged Packets*

A PHN estimates the channel quality from its own perspective and does not interact with other PHNs while evaluating itself. Thus, errors may occur when the PHN estimates channel quality and determines the sets of predicted failed and successful one-hop neighboring nodes. As a result, two or more PHNs that are in each others' one-hop distance evaluate themselves as the best potential helper nodes to relay the tagged packet. In such an event, simultaneous CRBs are performed during an

[1] Set $\mathcal{A}_{xy}$ is determined by node x, which consists of both reported and predicted failed nodes that are in good channel condition with node y from the perspective of node x.

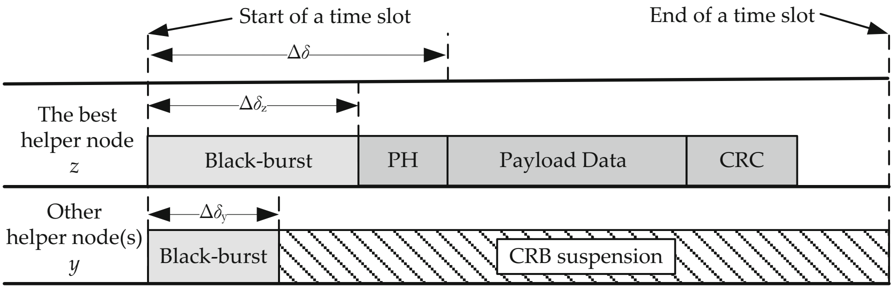

Fig. 6.3 CRB performed by the best helper node and suspension of CRB(s) from the other potential helper node(s) that is (are) not within the one-hop distance from the transmitting helper node

unreserved time slot which results in transmission collisions and waste cooperation opportunities. To avoid such undesired events, a node uses an energy-burst or channel jamming signal, also known as black-burst [7]. In doing so, after finding itself as the best potential helper node, node z transmits a black-burst for a random time interval, say $\delta_z \Delta$ seconds, from the start of a time slot, where δ_z is randomly drawn from set $\{1, 2, \cdots, \delta\}$ and Δ is a fixed and small time duration (such as a slot time in the IEEE 802.11 based MAC protocols). As soon as node z finishes transmitting the black burst, it listens to the channel. If the channel is idle during the listening time, it then relays the tagged packet. This is illustrated in Fig. 6.3 where node y, with smaller black-burst period, suspends its CRB after detecting the channel to be busy due to a longer black-burst period from node z. With a large δ value, the probability of two or more PHNs choosing the same black-burst period can be minimized. Note that the sum of $\delta\Delta$ and the transmission time of a CRB packet should not be greater than the duration of a time slot. As well, repeated transmission of the FI during CRB is unnecessary as a node owns a time slot to transmit a complete packet with its FIs. Hence, a C-Type packet is transmitted during CRB from the best helper node that consists of a PH, payload data and CRC, as discussed in Sect. 5.2.1. The absence of FI compensates for the black-burst period (as well as time to listen the channel) and will not affect the normal operation of D-TDMA.

Thus, performing CRB after the transmission of black-burst signal for random time interval reduces transmission collisions from two or more PHNs. However, transmission collisions occur if two or more PHNs that are not in each other's one-hop distance evaluate themselves as the best helper nodes. In such a case, they fail to sense each others' black-burst signals and perform CRB after finding the channel idle. Such an undesired event results in transmission collisions at their common one-hop neighboring nodes. However, such a transmission collision degrades the CRB performance only if it occurs at PDNs, as PHNs nodes are not the target receivers during the CRB.

In the next section, we present simulation results to evaluate the performance of the proposed CRB schemes.

6.5 Simulation Results

Simulations are performed in MATLAB considering the similar networking scenarios, road segment and node mobility, as described in Sect. 5.4. As the channel estimation, discussed in Sect. 6.1.1, is valid for integer m values, here we consider $m = 2$ which is reasonable for $R \leq 100$ m. Performance of CRB schemes with optimal helper selection (CRB-OPT) and helper selection based on channel prediction (CRB-HSCP) is evaluated and compared with the D-TDMA MAC. The following performance metrics are considered to study the transmission reliability and efficiency of CRB:

1. *Packet received rate*, which is the ratio of the number of nodes in the area of interest, i.e., one-hop neighboring nodes of a source node, that received the tagged packet before it expires, either directly from the source node or through cooperative relay broadcasting, to the total number of nodes in the area of interest [8]. It gives the percentage of the number nodes in the area of interest that successfully received the tagged packet and reflects the probability of a node to receive the tagged packet before it expires;
2. *Packet delivery ratio*, which is the ratio of the number of packets that are successfully received by the required percentage of nodes in the area of interest over the total number of broadcast packets [8]. The ability of a broadcast service to disseminate a packet to achieve the required QoS is represented by packet delivery ratio. Hence, we consider three levels of QoS requirements—the tagged packet must be delivered to 50, 75, and 99% of nodes which are in the area of interest;
3. *Normalized number of retransmission attempts*, which is the ratio of the number of broadcast attempts to the maximum number of possible broadcast attempts of a packet in a frame to achieve the required QoS. The efficiency of a broadcast service can be represented by the number of broadcast attempts to achieve the required QoS for a given packet. In CRB, a packet is rebroadcast during all available unreserved time slots before the packet expires or until the end of the corresponding time frame. Thus, the maximum number of possible broadcast is the number of available unreserved time slots in the time frame. Here, we consider a large frame size F with respect to the average number of THS nodes sharing a time frame, $\overline{N}_T$. Thus, from (4.6), the maximum number of possible broadcast is given by $F - N_T$.

Figures 6.4 and 6.5 show the packet received rate at various channel conditions represented by path-loss exponent values (α). It is observed that when the channel condition is good with $\alpha = 2$, the packet received rate of D-TDMA MAC reaches 1. This is because, with $\alpha = 2$, a source node is capable of disseminating packets directly to all of its one-hop neighbors and does not require node cooperation to rebroadcast the packet. However, as the channel condition degrades, the packet received rate decreases to 0.88 and 0.29 for $\alpha = 3$ and 4 respectively. At a moderate channel condition with $\alpha = 3$, transmission failures from the source node increase,

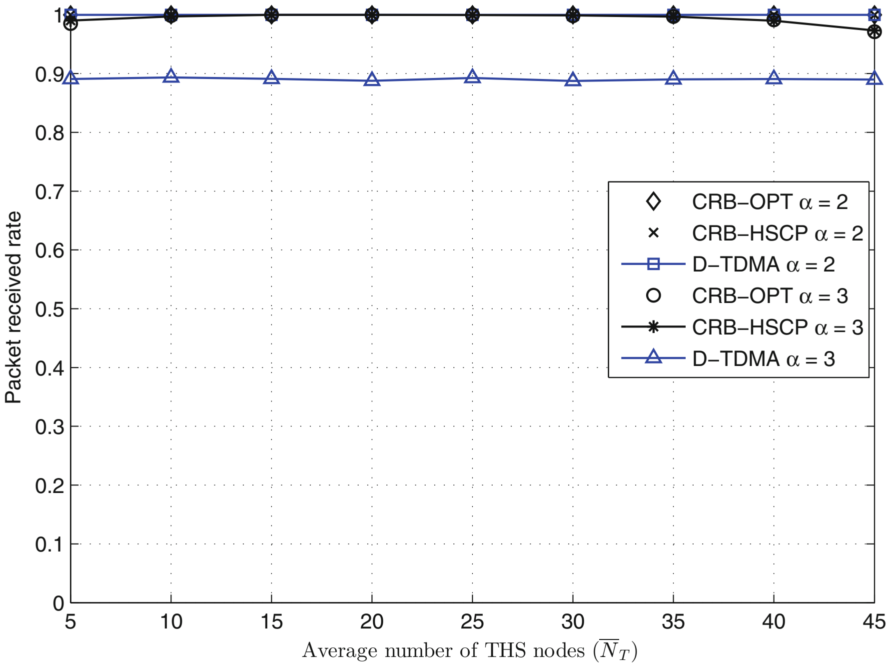

Fig. 6.4 Packet received rate in D-TDMA MAC, CRB-OPT and CRB-HSCP with $\alpha = 2$ and 3 [1]

which results in a decrease in packet received rate. On the other hand, the CRB schemes recover from the transmission failures and increase packet received rate to 1. At a poor channel condition with $\alpha = 4$, the packet received rate of CRB schemes are lower than that with $\alpha = 3$. The packet received rate decreases as the α value increases from 3 to 4. The packet received rate reaches its peak when the number of nodes in the area of interest is moderate with respect to the number of time slots in a frame.[2] When $\overline{N}_T$ value is small, there are no helper nodes to perform CRB or the number of PDNs is large and CRB is not effective. At a large $\overline{N}_T$ value, the number of unreserved time slots is not enough to serve all the PDNs. Hence, CRB is not effective at a small or large $\overline{N}_T$ value.

Figures 6.6–6.11 show the packet delivery ratio for different QoS requirements and at various channel conditions. As D-TDMA MAC is capable of achieving a 99% delivery ratio at the good channel condition ($\alpha = 2$), the packet delivery ratio with $\alpha = 2$ are not included in the following analysis. The channel quality degrades

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[2]Here, we consider one-hop transmission distance in either direction of a source node as the area of interest, i.e., nodes distributed over length of $2R$ meters. Thus, the average number of nodes per two-hop set per frame, $\overline{N}_T$, is compared with the number of time slots per frame, F, such that $\overline{N}_T \ll F$ reflects a small number of nodes or a small $\overline{N}_T$ value and $\overline{N}_T \approx F$ reflects a large number of nodes or a large $\overline{N}_T$ value.

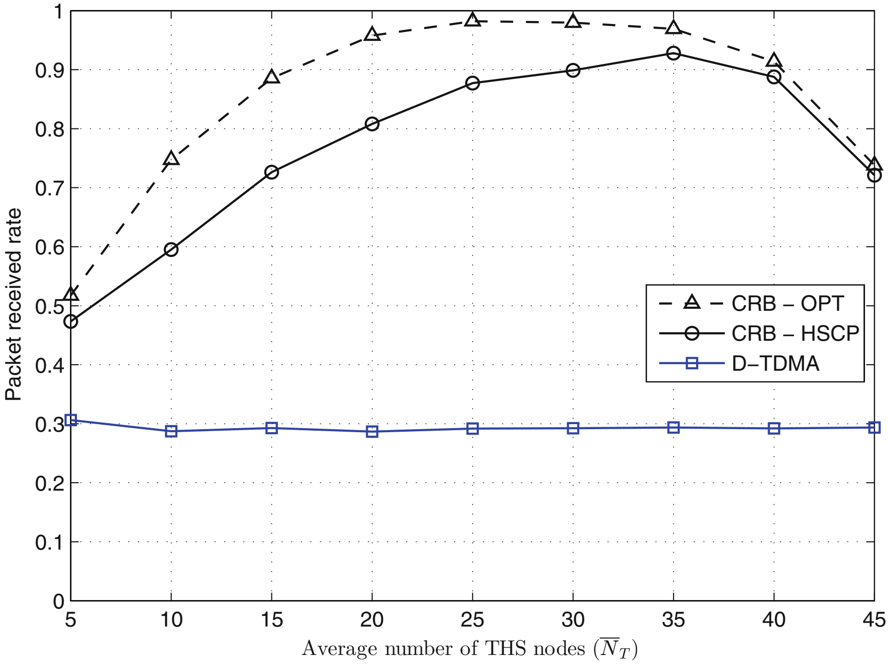

Fig. 6.5 Packet received rate in D-TDMA MAC, CRB-OPT and CRB-HSCP with $\alpha = 4$ [1]

when α value increases to 3 and 4 and consequently, D-TDMA MAC fails to achieve the required QoS. It can be observed from Fig. 6.7 that D-DTMA MAC can achieve only up to 75% QoS level with $\alpha = 3$. When the QoS requirement increases to 99%, the packet delivery ratio decreases to 0 for a relatively high number of nodes, as in Fig. 6.8. With the CRB schemes, on the other hand, the packet delivery ratio reaches to 1 even with 99% QoS requirement and at a larger number of nodes. This is because the tagged packet is repeatedly rebroadcasted until it expires, such that all the one-hop neighbors of the source node receive the packet. Furthermore, when the channel quality degrades ($\alpha = 4$), as in Figs. 6.9–6.11, D-TDMA is not even effective to meet the 50% QoS requirement. In contrast, the packet delivery ratio using CRB schemes improves when the average number of THS nodes is moderate. However, the packet delivery ratio is low when the average number of THS nodes is relatively large or small.

Figures 6.12 and 6.13 show the normalized number of retransmission attempts of the CRB schemes. The normalized number of retransmission attempts reaches 1 when the number of nodes is relatively large and the channel is in a poor condition. This is due to the fact that all the unreserved time slots are used for CRB to deliver the packet to a large number of failed nodes, which is common in a poor channel condition. However, due to the lack of helper nodes to perform CRB, the normalized number of retransmission attempts is less than 0.1 when the number of nodes is relatively small.

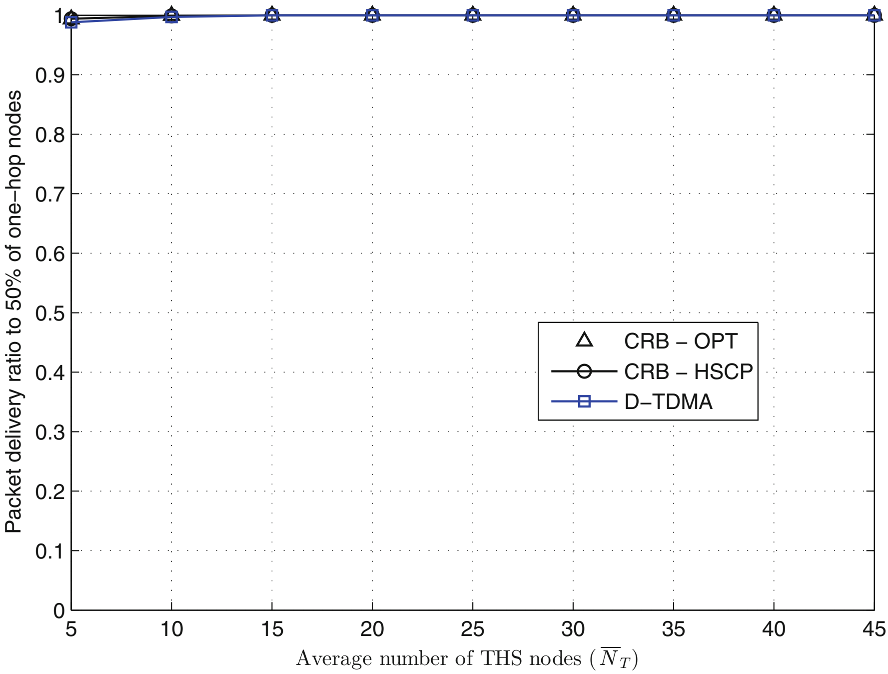

Fig. 6.6 Packet delivery in D-TDMA MAC, CRB-OPT and CRB-HSCP with $\alpha = 3$ such that the 50% QoS requirement is achieved within a duration of one time frame [1]

It can be observed from Figs. 6.4, 6.6, 6.7, 6.8 and 6.12 that at a good ($\alpha = 2$) or moderate ($\alpha = 3$) channel condition, the CRB-HSCP scheme performs equally well in comparison with the CRB-OPT scheme. However, as the channel quality degrades with $\alpha = 4$ as in Figs. 6.5, 6.9, 6.10, 6.11 and 6.13, the channel prediction is not as effective as that of the earlier cases. Accordingly, two or more PHNs evaluate themselves as the best helper node to perform CRB in a given unreserved time slot, which results in transmission collisions. Such prediction errors and transmission collisions lead to failed CRBs in CRB-HSCP when the channel is in a poor condition, which are not considered in CRB-OPT. Thus, CRB-HSCP doest not perform well at the poor channel conditions and performs more CRBs than the CRB-OPT scheme. However, the performance of the CRB-HSCP scheme is significantly higher than that of D-TDMA MAC in all the cases. It even reaches up to that of CRB-OPT scheme, the upper limit, when the number of nodes is relatively large in the network.

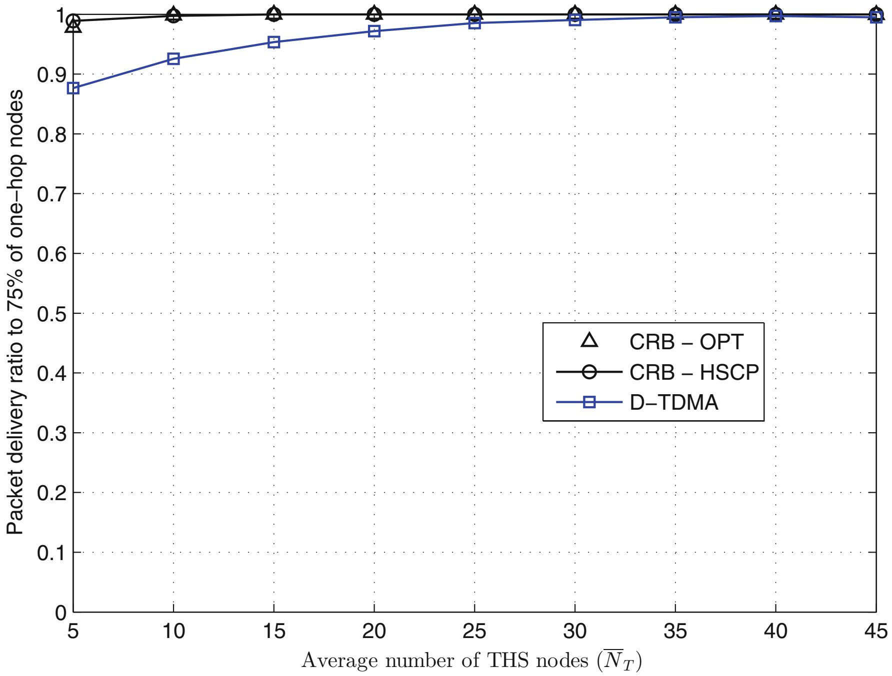

Fig. 6.7 Packet delivery in D-TDMA MAC, CRB-OPT and CRB-HSCP with $\alpha = 3$ such that the 75% QoS requirement is achieved within a duration of one time frame [1]

6.6 Summary

In this chapter, we present a node cooperation based makeup transmission framework for VANETs, referred to as cooperative relay broadcasting (CRB). The proposed CRB framework is a generic framework and can be implemented with any given helper selection scheme. To study the advantages of the proposed CRB framework, we first propose a helper selection scheme that requires a perfect knowledge of channel information and provides an upper bound of the CRB performance. Furthermore, we propose a realistic helper selection scheme that uses channel prediction based on the first-order two-state Markov channel, to evaluate helper nodes to perform CRB. Our analysis shows that the proposed CRB framework improves the reliability of the broadcast service in VANETs.

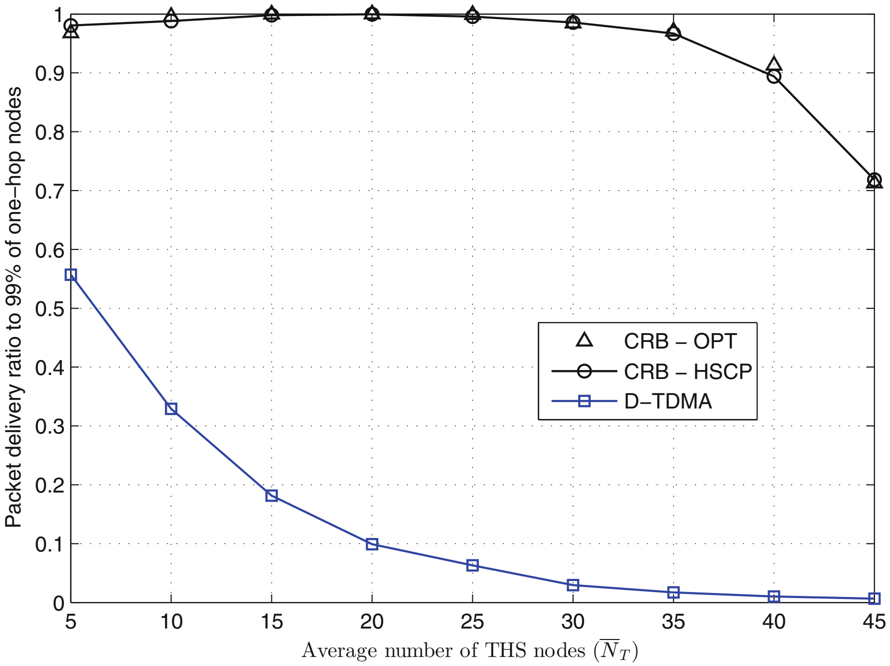

Fig. 6.8 Packet delivery in D-TDMA MAC, CRB-OPT and CRB-HSCP with $\alpha = 3$ such that the 99% QoS requirement is achieved within a duration of one time frame [1]

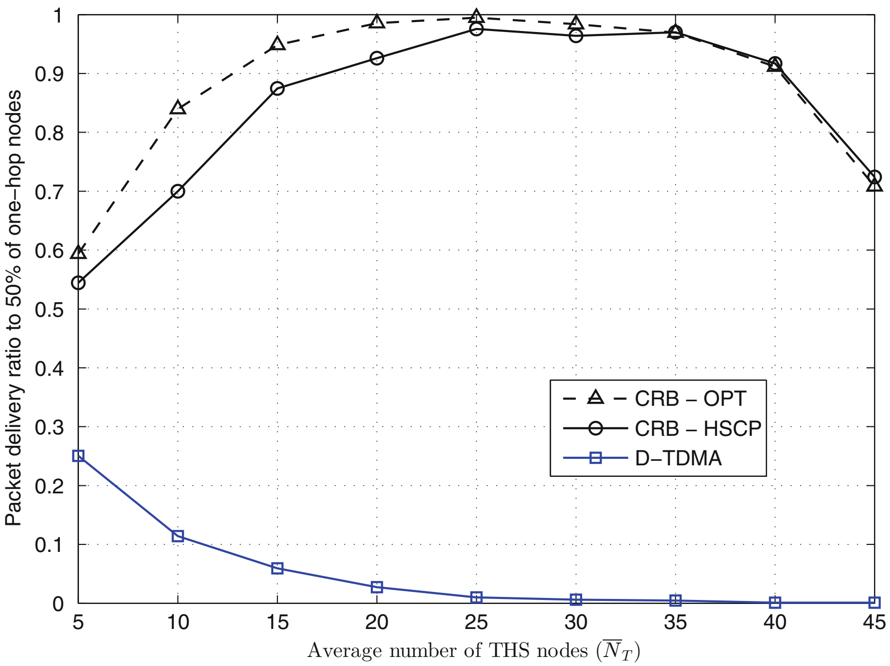

Fig. 6.9 Packet delivery in D-TDMA MAC, CRB-OPT and CRB-HSCP with $\alpha = 4$ such that the 50% QoS requirement is achieved within a duration of one time frame [1]

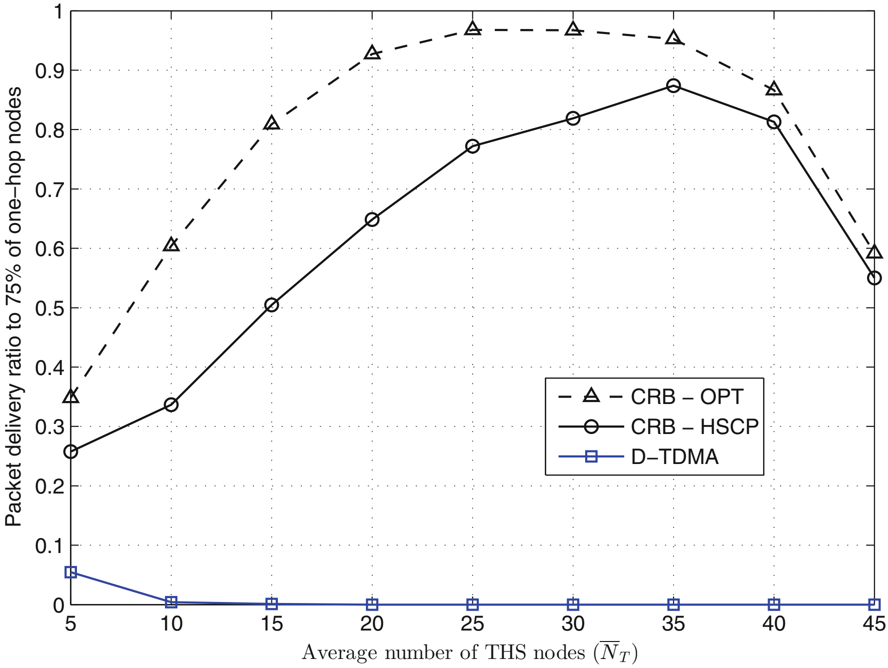

Fig. 6.10 Packet delivery in D-TDMA MAC, CRB-OPT and CRB-HSCP with $\alpha = 4$ such that the 75% QoS requirement is achieved within a duration of one time frame [1]

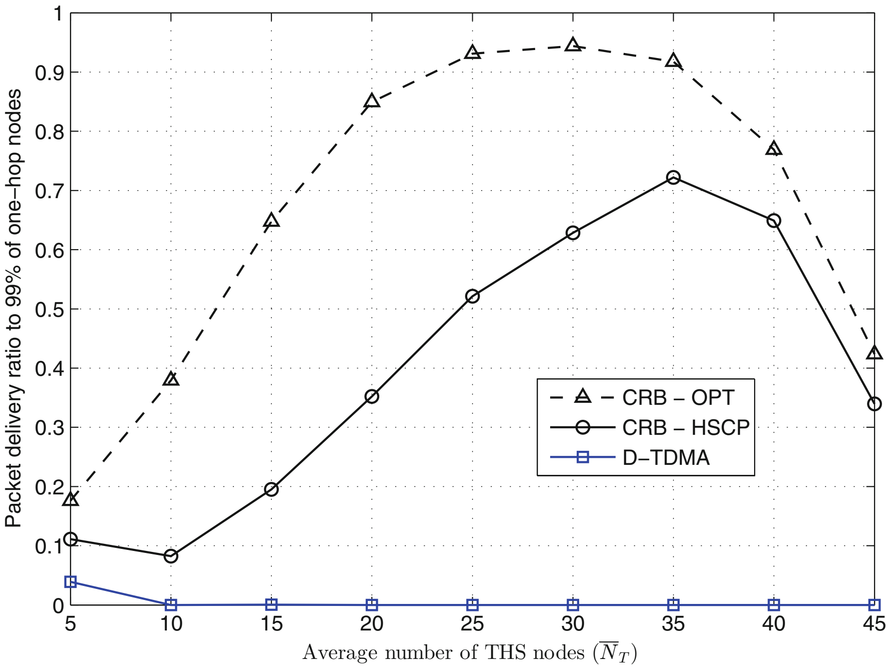

Fig. 6.11 Packet delivery in D-TDMA MAC, CRB-OPT and CRB-HSCP with $\alpha = 4$ such that the 99% QoS requirement is achieved within a duration of one time frame [1]

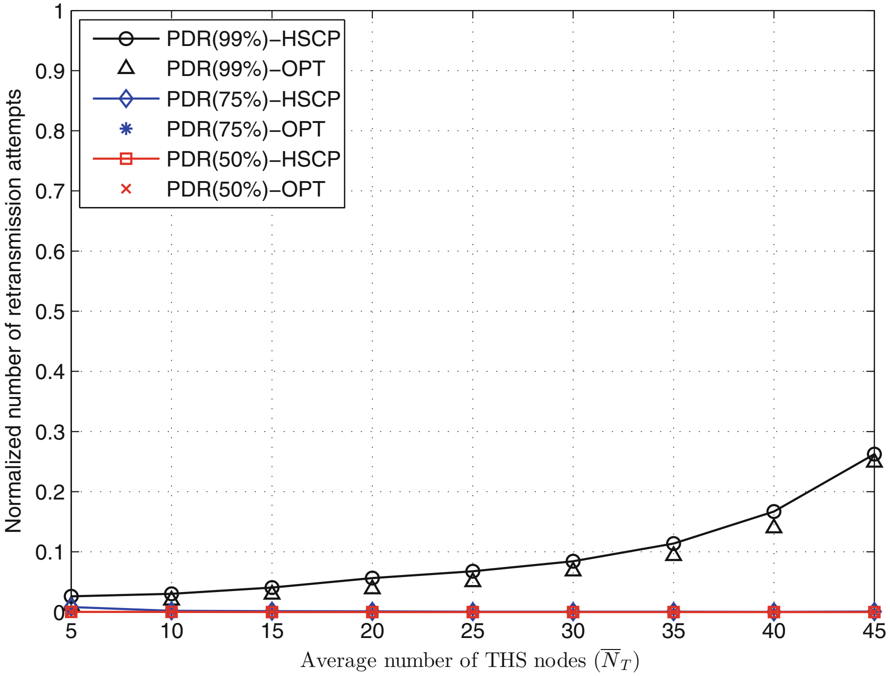

Fig. 6.12 Normalized number of retransmission attempts over the number of unreserved time slot in CRB-OPT and CRB-HSCP with $\alpha = 3$ [1]

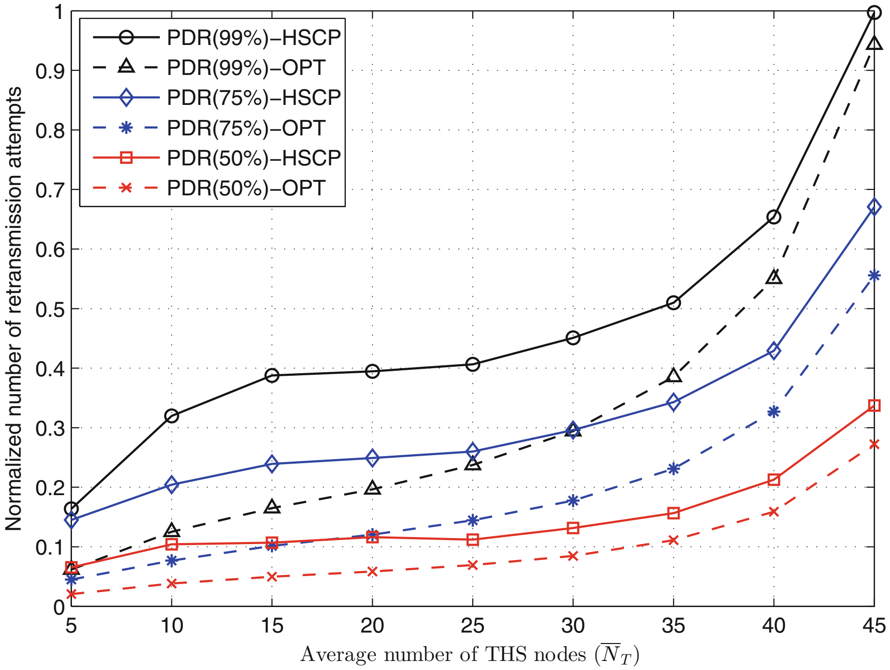

Fig. 6.13 Normalized number of retransmission attempts over the number of unreserved time slot in CRB-OPT and CRB-HSCP with $\alpha = 4$ [1]

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Chapter 7
Conclusions and Future Works

7.1 Conclusions

Vehicular ad hoc networks will be an essential component of intelligent transportation systems, to enable a wide range of mobile distributed applications to improve the safety and efficiency of vehicle transportation and support onboard passenger infotainment. The existing MAC approaches for VANETs are not free from packet dropping and throughput reduction due to the dynamic networking conditions and are not always suitable to support the wide range of mobile distributed applications. On the other hand, link-layer node cooperation can be used to improve the performance, establishing a more efficient, robust and reliable communication among nodes. However, the existing link-layer node cooperation schemes are not suitable for the vehicular dynamic networking conditions and cannot be applied directly to VANETs. Thus, this book presents node cooperation frameworks at the MAC layer of VANETs to provide efficient and reliable communication to support the wide range of applications with strict service requirements, and to provide more robust communication to tackle the dynamic networking conditions.

We propose and analyze a cooperative MAC protocol, referred to as Cooperative ADHOC MAC, for distributed TDMA MAC in vehicular networks. In CAH-MAC, upon detecting a transmission failure between a pair of source and destination nodes, a neighboring node offers cooperation to relay the packet to the destination node during an unreserved time slot. When the relative node mobility is negligible, numerical results show that the CAH-MAC performs better than the existing D-TDMA MAC under similar networking conditions. As unreserved time slots are used for retransmission, throughput improvement is achieved. In addition, as a packet is retransmitted by a helper node as oppose to the retransmission by the source node in the next frame, the transmission delay is reduced and packet dropping rate is decreased. Numerical results demonstrate that CAH-MAC performs better

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when the number of nodes in a two-hop neighborhood is moderate as compared with the total number of time slots available in a frame. Furthermore, performance gain is significant for a moderate channel condition.

In a dynamic networking environment, node cooperation during unreserved time slots may lead to conflicts in the form of cooperation collisions, thus disrupting the normal operations of the D-TDMA MAC. To tackle such conflicts, we present a collision avoidance scheme for the CAH-MAC protocol, referred to as enhanced Cooperative ADHOC MAC (eCAH-MAC). In eCAH-MAC, the cooperative relay transmission phase is delayed, so that cooperation collisions can be avoided. It uses available bandwidth resources efficiently in the presence of time slot reservation attempts, which is a consequence of vehicular network dynamics, improving the performance of node cooperation at the MAC layer protocol. Our analysis shows that the effectiveness of node cooperation decreases with an increase in the number of nodes mainly due to an increase in the number of reservation attempts. However, as time slot reservations are allowed despite of the scheduling of cooperative relay transmission, eCAH-MAC does not disrupt the normal operations of the D-TDMA MAC. Furthermore, we consider a practical channel model and vehicle traces to perform extensive simulations. We demonstrate the efficiency and robustness of eCAH-MAC in a dynamic networking environment. Through mathematical analysis and simulations, we observe that eCAH-MAC is capable of avoiding cooperation collisions by suspending a cooperative relay transmission phase, which allows more nodes, seeking their own time slots, to efficiently reserve unused time slots.

We present a node cooperation based makeup transmission framework for D-TDMA MAC, referred to as cooperative relay broadcasting (CRB). In the proposed CRB scheme, nodes with a packet from a source node relay the packet until it expires, making it suitable for delay sensitive safety applications with strict QoS requirements. The packets are forwarded by the best helper nodes during unreserved time slots. Accordingly, we first propose an optimal helper selection scheme that requires accurate channel state information to select the best helper nodes. The proposed helper selection scheme provides an upper bound of the CRB performance, which can be used as a benchmark for performance evaluation. Furthermore, we propose a channel prediction based helper selection scheme that uses the local information to estimate the channel quality and selects the best helper nodes. Through extensive simulations, we observe that CRB is useful in a poor channel condition. Our analysis shows that the channel prediction based helper selection scheme performs equally well in comparison with the optimal helper selection scheme, when the channel condition and the number of nodes in the area of interest are moderate. However, as the channel quality degrades, due to errors in channel prediction and occurrence of transmission collisions, the performance of the proposed helper selection is lower than the maximum performance limit, but is significantly better than that of D-TDMA MAC.

7.2 Open Issues for Further Research

Introduction of node cooperation focusing D-TDMA MAC leads to several other research issues that are not discussed in this book. In the following, we present some of these open issues as a research direction for further research.

7.2.1 Enhancing D-TDMA MAC Schemes

The existing D-TDMA MAC protocols for VANETs do not work efficiently when the number of nodes sharing a frame is too small or large as compared to the total number of time slots available in a frame. It is necessary to develop a scheme to enhance the performance of D-TDMA MAC and make it more robust to tackle variation in vehicle density. One possible way to tackle such issue is by varying the transmission power (P_t), which consequently varies the transmission range (R) and adjusts the number of nodes in a given two-hop set sharing a frame. Hence, how to determine the occurrences of such an undesired event and how to implement a scheme to resolve the event need further investigation. In addition, the existing D-TDMA MAC protocols suffer from the unnecessary loss of time slots due to a temporal channel fading. A node, after suffering from a transmission collision or channel error or both, releases its time slot to avoid conflicts. However, release of time slots due to channel errors may not be necessary and degrades the system performance. Hence, it is an important research topic to differentiate transmission collisions and channel errors in D-TDMA MAC, in order to avoid unnecessary loss of time slots and improve the system performance. Furthermore, to avoid negative impacts due to the unnecessary release of time slots, a maximum allowable transmission limit can be set, such that a node releases its time slot only if it does not detect its ID for a given number of consecutive frames due to poor channel conditions. With the aforementioned provisions, the proposed node cooperation schemes in this book are expected to be more effective in correcting the transmission failures due to a poor channel condition.

7.2.2 Efficient Channel Prediction for CRB

A more efficient helper selection scheme to perform CRB can be considered to improve the performance of the proposed CRB framework. Advance signal processing and/or network coding can be implemented to achieve an accurate channel estimation. Such accurate channel estimation will enhance the performance of the proposed CRB framework, reduce the performance gap with the upper bound from optimal helper selection scheme, and result in a more efficient, reliable and robust broadcast service.

7.2.3 Cooperation in Multi-channel MAC

This book focuses on node cooperation for D-TDMA which operates in a single frequency channel. An investigation regarding the possibility of node cooperation for multi-channel MAC in VANETs is an interesting research direction. The existing D-TDMA multi-channel MAC, such as VeMAC, is capable of providing a collision free broadcast service in the control channel (CCH). A VeMAC-enabled node broadcasts packets of safety applications in the CCH and gets ACKs (or NACKs) from all of its one-hop neighbors which own time slots. Also, it advertises its services, to be provided in a service channel (SCH), in the CCH (see Appendix A for detail about multi-channel operations, including multi-channel MAC protocols and cooperation in such multi-channel environments). Provider and user exchange packets related to non-safety applications in the SCH(s), based on negotiations in the CCH. However, channel coordination for VeMAC, to avoid a channel conflict problem, is not defined in [1]. A channel conflict arises due to the lack of channel coordination when two or more providers attempt to use the same service channel at the same time. When a new $s-d$ pair[1] agrees to use time slot(s) of an SCH, which was already agreed on by a different $s-d$ pair, a channel conflict problem occurs. This is due to the lack of coordination among nodes (such as exchanging channel usage information) and relative mobility among the nodes. In VeMAC, when channel conflicts occur, the provider (which first reserves the channels) aborts the agreed negotiation, to avoid the possible collisions, and the new $s-d$ pair gets the channel access.

Such a conflict is illustrated in Fig. 7.1, where provider X offers its service to user D_1 in the control channel. The service is offered at a service channel during time slots $\{4, 8\}$. However, before user D_1 acknowledges, provider Y and user D_2 agreed to use time slots $\{5, 6, 8\}$ of the service channel. User D_1, which is not in transmission range of Y and D_2, agreed to get the offered service from provider X. If both the services are offered, there will be collision at user D_2 during time slot 8 of the service channel. To avoid such collisions in VeMAC, provider X aborts its service even though it offered its service before provider Y. Suspension of an ongoing service by a provider in the middle of transmission is not be suitable for real-time applications with a strict delay requirement. Furthermore, the provider may require to advertise its service and renegotiate with user(s) due to the suspension. Hence, reservation of a service channel must be done on a first-offered-first-served basis. In other words, a newly offered service should not get access to the channel interfering the ongoing services. Hence, how to implement a node cooperation approach, for instance deploying cooperation among one-hop nodes to exchange the channel usage information, to solve the channel conflict problem needs further research.

[1] A pair of provider and user is denoted as an $s-d$ pair.

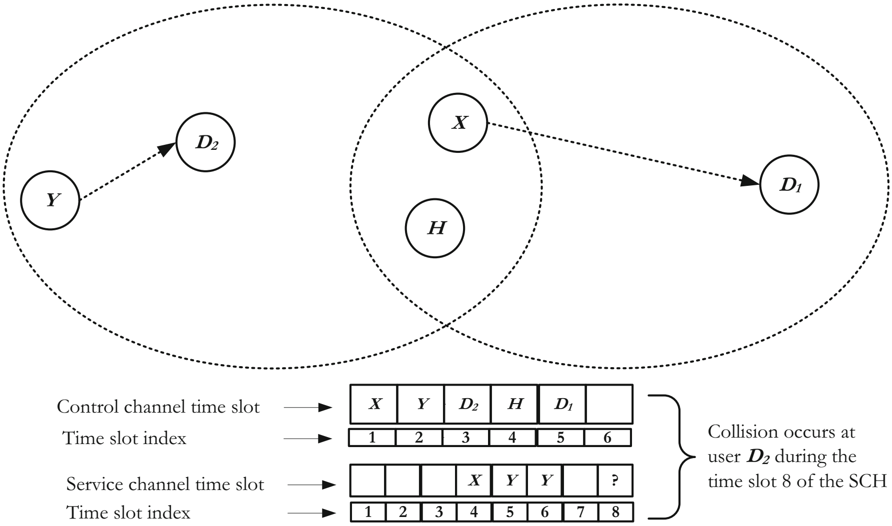

Fig. 7.1 Channel conflict problem in VeMAC

Reference

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Appendix A
Multi-channel Operation in VANETs

The Dedicated Short Range Communication (DSRC) spectrum in 5.9 GHz band consists of seven channels [1]. Figures A.1 and A.2 show the allocated channels and corresponding power allocation, respectively, in the DSRC spectrum. Out of seven available channels, *Channel 178*, also known as the control channel (CCH), is allocated to exchange high priority safety messages and other control information. Two channels at the edges are allocated for safety related applications and reserved for the future use. The remaining four channels, known as the service channels (SCHs), are allocated for non-safety related applications. It is worth noting that vehicles negotiate in the CCH to determine which SCH to be tuned into for exchanging packets. After the nodes negotiate, packets are exchanged in the negotiated SCH.

A.1 Multi-channel Operations in VANETs

In a VANET multi-channel environment, a set of packets that are associated with the safety and non-safety related applications and to be transmitted in SCHs is known as a *service*. A *provider* is a source node which offers a service and transmits associated packets to its neighboring nodes, referred to as *users*. A provider and users of a service negotiate in the CCH regarding the use of an SCH to transmit and receive the corresponding packets, respectively. The provider establishes a WAVE-mode Basic Service Set (WBSS) in a distributed manner by transmitting an announcement of the service through WAVE Service Advertisement (WSA). The announcement is performed in the CCH, and the provider chooses an SCH where the service is to be provided. A user, if interested in the service, joins the WBSS established by the provider. In the wireless access in vehicular environment (WAVE)/IEEE 1609.4 standard [2], which governs the multi-channel operations, the process of choosing

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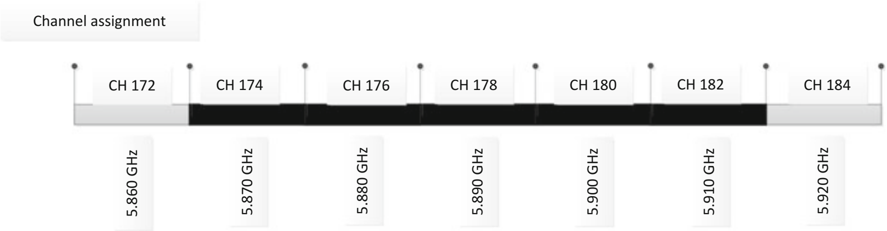

Fig. A.1 Spectrum allocation for DSRC channels

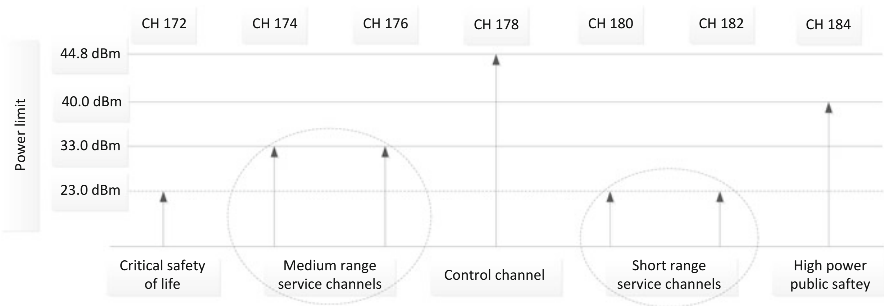

Fig. A.2 Power allocation in DSRC channels

an SCH to provide a service is not specified; however, it suggests that the provider should choose an SCH which has the least interference from its neighboring nodes (i.e., not used in the two-hop transmission distance of the provider) [3].

A.2 Multi-channel MAC (MCM) Protocols

In VANETs, a multi-channel MAC protocol has to operate in the presence of a single control channel (CCH) and multiple service channels (SCHs). Based on the multi-channel operations, governed by wireless access in vehicular environment (WAVE)/IEEE 1609.4 standard [2], several MCM protocols using one or two radios have been proposed for VANETs . With a single radio [3–8], a node will miss the safety message broadcast in the CCH if it is tuned to SCH. In addition, it causes the hidden and exposed terminal problems when an $s-d$ pair[1] tuned to different SCHs fail to coordinate in the CCH due to the usage of a single transceiver. Mak et al., in [9], propose an MCM protocol with one radio and a central controller to solve coordination issues. However, the use of such a central controller, in the form of coordinating and/or service access point, may not be always suitable for VANETs, specifically for vehicle-to-vehicle communications.

[1]A pair of provider and user is denoted as an $s-d$ pair.

When two transceivers are used, one transceiver is dedicated to transmit and receive the high priority safety messages and other control signals in the control channel, and the other transceiver is tuned to one of the available service channels. Nodes negotiate in the control channel regarding the use of available service channels. A cluster based MCM protocol is proposed in [10], alleviating contention based channel access, to provide QoS satisfaction for delay and throughput sensitive applications. However, operations of such scheme depend on the cluster head. Such dependency is not suitable when the mobility among nodes is high and results in frequent re-selections of the cluster head. In contrast, VeMAC [11] allows to form a cluster among neighboring nodes that are within the two-hop transmission distance. Clusters are formed in a distributed manner and there are no cluster heads to coordinate among nodes. In addition, VeMAC provides reliable broadcast service to support safety related applications and helps to announce a service in a contention free manner. However, as an SCH is selected based on the distance between the provider and user, VeMAC suffers from the channel conflict problem. The channel conflict problem occurs when two or more providers attempt to access the same service channel due to the lack of channel usage information. In addition, broadcast or multicast services in SCHs, providing a service to more than one user in the network, are not defined in VeMAC.

A.3 Cooperation in Multi-channel MAC

In [12], the authors propose CAM-MAC, a four-way handshaking protocol to solve the channel conflict problems. Such a scheme allows cooperation from neighboring nodes of an $s - d$ pair, providing the channel usage information. The $s - d$ pair negotiates, based on the channel usage information gathered locally, in the dedicated control channel to select the least interference channel and solve the channel conflict problem. In [13] a similar problem, the channel selection problem, is discussed. In addition, the authors propose a cooperative scheme, based on CDMA code distribution, to solve the channel conflict problem as well as the hidden and exposed terminal problems. However, the proposed solution works only for point-to-point communication and is not broadcast friendly, which makes it unsuitable to implement in VANETs. In [14], the authors propose broadcast enhanced CAM-MAC with power adoption and broadcast prediction schemes. Such schemes make CAM-MAC suitable to provide broadcast/multi services as well as point-to-point services in a multi-channel environment. However, the performance of CAM-MAC degrades when the mobility among neighboring nodes increases [15]. Thus, CAM-MAC and its derivatives are not suitable for VANETs as high mobility among nodes and frequent link breakage are highly likely. Channel selection for a multi-channel MAC in VANETs is not specified in the IEEE/WAVE 1609.4 standard. In [3], the authors introduce CRaSCH, an efficient channel selection schemes for VANETs multi-channel MAC protocol. In CraSCH, a channel selection scheme, based on cooperation among the one-hop neighborhood nodes, is proposed to avoid the channel conflict problem. However, this scheme is based on a single-transceiver MCM. Hence, CraSCH needs further investigation to implement in a realistic VANETs scenario enabled with two-transceiver MCM. Thus, the existing node cooperative schemes in the multi-channel environment are not suitable for the high mobility scenario. Hence, for multi-channel operations, VANETs require more from link-layer node cooperation, specifically to solve channel coordination issues and make it broadcast friendly.

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Appendix B
Parameters in VISSIM Simulation

VISSIM is a well-known microscopic multi-modal time-step and behaviour based traffic simulator that is widely used to model urban traffic and public traffic operations [1]. It takes various parameters such as geometry of road networks, lane change configuration, locations and rules of traffic signal, presence and behaviour of pedestrians, etc., to model traffic behaviour. The road networks can be user defined, constructed using the graphical user interface functions of VISSIM, or replicated using aerial photographs of an actual road network. With such inputs, VISSIM generates various data such as vehicle information and status, travel time, lane change activities, etc., that are useful for effective planning in traffic and transportation engineering. Moreover, vehicle traces can be used in various other fields such as communication network planning to evaluate the systems and algorithms in vehicular networks, as in this book. The VISSIM traffic simulator mainly concerns with drivers' behaviours in following the headway vehicles, also known as car following logic, and lane change logic [1], which is discussed in the following sections.

B.1 Car-Following Model

The car following logic is based on the continued work of Wiedemann for car-following process [2] and Wiedemann and Reiter [3] for lane-changing, which consists of a psycho-physical car following model for longitudinal vehicle movement and a rule-based algorithm for lateral movements. The Wiedemann car-following model assumes that one of the four driving mode that drivers can adopt, namely:

- ***Free-driving***: In this mode, drivers drive without any influence of any other vehicles such that s/he will first reach a certain speed, then maintain the constant speed. However, speed varies due to imperfect control.

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- ***Approaching***: In this mode, drivers adopt the speed of a preceding vehicle, which is lower than that of its own speed. On doing so, drivers apply declaration to maintain a minimum safety distance between two vehicles.
- ***Following***: In this method, drivers maintain zero acceleration or declaration and the minimum safety distance while following their preceding vehicles. However speed varies due to imperfect control.
- ***Braking***: In this mode, drivers apply medium to high deceleration to maintain safety distance with the preceding vehicles. This mode is adopted to reduce the speed suddenly which reacting to the events such as, sudden lane change of third vehicle, application of sudden brake by the preceding vehicle, etc.

In addition to the driving modes, the car following behavior in VISSIM also considers the number of time steps per second to perform any decision. In VISSIM 5.04, users can choose from one to ten time steps per second. The higher the number of time steps per second the more accurate results of the simulation and the slower the simulation time. Based on the number of time steps and driving mode, two versions of car-following model is used VISSIM, namely Widemenn74 and Widemenn99 models. Widemenn74 car-following model is applied for urban roads and traffic condition, while Widemenn99[1] car-following model is applied for highway traffic condition. This book focuses on analyzing the performance of vehicular communication algorithms in a highway scenario, we will mainly focus on Widemenn99 car following model which includes the calibration of ten parameters, namely CC0–CC9 as in the Table 5.2, to adopt driving modes as required during the simulation.

B.2 Lane Changing Parameters

VISSIMS consists of two types of lane changing logics namely, necessary lane change and free lane change. A necessary lane change is defined in VISSIM as to change lane is necessary for a vehicle to reach the next connector in its route. The free lane change considers a lane change of a vehicle in order to maintain safety distance. A driver decides to perform free lane change, to a target lane, if s/he is unable to maintain desired safety distance with a preceding vehicle. This safety distance depends on the speed of lane changing vehicle and trailing vehicle in the target lane. Important parameters to calibrate lane changing behaviour are listed in Table 5.2.

[1]The Wiedemann99 is an improvised version of Wiedemann car following model that provides more control of the car following behaviour specific for a highway traffic [1].

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