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Cross-Layer Treatment of Mobility for Mobile Ad Hoc Networks

Kazi Atiqur Rahman
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Cross-Layer Treatment of Mobility for Mobile Ad Hoc Networks

By

Kazi Atiqur Rahman

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DECLARATION OF CO-ATHORSHIP

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates some materials part of which are results of joint researches. The investigations and evaluations done throughout this thesis used some technologies that were developed in the WiCIP research laboratory. The investigations were supported by collaborative help from my colleagues in WiCIP lab in the form of advice, critiques, and mentoring. This thesis also incorporates the outcome of joint research undertaken in collaboration with Khaja Shazzad, Dr. Nabih Jaber, William Cassidy, Kazi Aminur Rahman, and Matthias Lott under the supervision of Professor Dr. Kemal E. Tepe. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of co-authors was primarily through the provision of suggestions, comments, critiques, verification and other supports.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-authors to include the above material(s) in my thesis.

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II. Declaration of Previous Publication

This thesis includes parts from 5 original papers that have been previously published/submitted for publication in peer reviewed journals, as follows:

Thesis Chapter	**Publication**
Part of Chapter 5	N. Jaber, **K. A. Rahman**, W.G. Cassidy, K. E. Tepe “Reliable MAC Layer Designs for Vehicular Networks”, 26th Queen’s Biennial Symposium on Communications, The Donald Gordon Centre, Queen’s University, Kingston, ON, Canada, May 27 – 29, 2012.
Part of Chapters 2 and 5	**K.A. Rahman**, N. Jaber, and K.E. Tepe, “Markov Analysis of the Mobile Hidden Station Problem in MANET”, The 7th IWCMC, Istanbul, Turkey, 05-08 July 2011.
Part of Chapters 5	**K.A. Rahman**, K.M. Shazzad, and K.E. Tepe, “Analyzing Sliding Frame Reservation-Aloha MAC Protocol against Mobile Hidden Station Problem in MANET”, The 24th CCECE, Niagara Falls, ON, Canada, 08-11 May 2011.
Part of Chapters 4	**K.A. Rahman**, K.M Shazzad, and K.E. Tepe, “A Probabilistic Measure of Extended Reservation Aloha MAC Protocol Against Some MAC Problems in

and 5	MANET", IEEE ISCI, Kuala Lumpur, Malaysia, 20-22 March 2011.
Part of Chapters 4 and 5	**K.A. Rahman**, M. Lott, K. Aminur Rahman, and K.E. Tepe, "Characterization of the Adverse Effect of Neighborhood Capture in MANET and on the way to a Remedy", IEEE EIT, IEEE Xplore doi: 10.1109/EIT.2009.5189640, pages 344-348, Windsor, Ontario, Canada, June 2009.

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ABSTRACT

The current era of mobile communication is passing through the days of rapidly changing technologies. Such an evolving promising technology is mobile ad hoc networks (MANETs). The communications in ad hoc networks are adversely affected by the link failures in the network layer, and by the hidden station, mobile hidden station, neighborhood capture and asymmetric radio link problems in the MAC layer. All the problems are highly affected by mobility of the stations. If the degree of mobility of any station in a route increases, the route life time decreases. That causes frequent link failures, and results packet retransmissions, additional latency and packet loss. An algorithm to include mobility in a routing protocol to reduce packet losses in a MANET is proposed in this thesis. The proposed algorithm estimates the number of packets that can traverse through the route before it breaks because of mobility. The algorithm is implemented in dynamic source routing protocol, and simulated in Network Simulator-2. The MHS problem arises if a station is hidden due to mobility. Asymmetric/unequal radio links in can occur in MANETs/VANETs for many reasons such as hardware limitations, power saving protocols, shadowing effects, dynamic spectrum managements. A MAC protocol named extended reservation Aloha (ERA) is proposed which partially solves these problems. Then, using the concept of ERA, another MAC protocol named extended sliding frame reservation Aloha (ESFRA), which addresses all the above mentioned MAC problems, is proposed in this thesis.

As safety critical information dissemination in DSRC/WAVE systems requires reliability and robustness, a network-MAC cross-layer information dissemination protocol is proposed in this thesis to address those issues. Although the layered architecture is still a good candidate for any design of wireless networks, the researchers are looking for some optimizations by interaction between neighbor layers which is called cross-layer design. So I proposed a network-MAC cross-layer algorithm, cross-layer extended sliding frame reservation Aloha (CESFRA), which solves mobility related problems, confirms low and deterministic end-to-end delay, and is robust and reliable in safety critical information dissemination up to 3rd hop. Discrete time Markov chain (DTMC) and OMNeT++ are used for all the MAC layer analyses.

DEDICATION

To my parents who always encourage me for higher studies, and keep me in their prayers.

To my wife and best friend "Shah Mst Nasrin Sultana" who stood beside me with her support all the way until this work was done.

To my sweet children "Subha Rahman Kazi and Ayaan Rahman Kazi".

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I feel a special gratitude and would like to acknowledge the advice and support from my supervisory committee members: Dr. Mohammed Khalid, Dr. Narayan Kar, and Dr. Ziad Kobti, for their valuable comments and for sharing their vast experiences with me in making my dissertation resourceful. I like to sincerely thank my external examiner: Dr. Ala Al-Fuqaha for agreeing to be my external examiner, and for his invaluably scholarly advice to complete my thesis.

I would like to thank my colleagues: Khaja Shazzad, Izhar Ahmed, Dr. Ishaq Gul Muhammad, Dr. Brajendra Kumar Singh, Dr. Nabih Jaber, William Cassidy, N.C. Doyle, Patrick Casey, Zahangir Toimoor, Ahmed El-Baba, Shawn Rupert, Sarab Al Rubeaai, Syed Sami, Mehmood Abd, Abdul Ghani Sayani Mohammad and Saneeha Ahmed in WiCIP LAB for their critical insights and enlightening discussions.

I would like to thank Andria Ballo for her administrative advices and supports throughout the period of my research.

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LIST OF ABBREVIATIONS/SYMBOLS

ACK	Acknowledgement
AFR	Asynchronous fixed repetition
AFR-CS	AFR by adding a carrier sensing (CS) mechanism
ALLT	Adaptive link life time
AODV	Ad hoc on-demand distance vector
APR	Asynchronous p-persistent repetition
ARL	Asymmetric radio link
ATPB	Adaptive M-ary tree algorithm with priority broadcast
BC	Basic channel
BSM	Basic safety message
b-slot	Back-off slot
CBR	Constant bit rate
CI	Cross-layer information
CLD	Cross-layer design
CTS	Clear-to-send
CESFRA	Cross-layer sliding frame reservation Aloha
CVSS	Cooperative vehicle safety system
DBTMA	Dual busy tone multiple access
DCF	Distributed coordination function
DSR	Dynamic source routing
DSRC	Dedicated short range communication
DTMC	Discrete time Markov chain
ERA	Extended reservation Aloha
ES	Exposed station
ESFRA	Extended sliding frame reservation aloha
FI	Frame information
GCR	Global channel release
HS	Hidden station
IHN	Information hop number
LLT	Link life time

MAC	Medium access control
MANET	Mobile ad hoc network
MAOD	Mobility assessment on-demand
MHS	Mobile hidden station
MSD	Message set dictionary
NC	Neighborhood capture
Node/Station	A user terminal or workstation or laptop or any ad hoc module
NS-2	Network simulator 2
ODMRP	On-demand multicast routing protocol
OBU	On-board unit
PHY	Physical layer
POC	Positive orthogonal codes
R-Aloha	Reservation Aloha
RLT	Route life time
RSSI	Received signal strength indication
RSU	Road side unit
RTS	Request-to-send
SAE	Society of automotive engineers
SF	Sliding frame
SFR	Synchronous fixed repetition
SFRA	Sliding frame reservation Aloha
SPR	Synchronous p-persistent repetition
TCP	Transport control protocol
TDD	Time division duplex
TDM	Time division multiplexing
TLLT	Threshold link life time
UDP	User datagram protocol
UI	Upper layer information
VANET	Vehicular ad hoc network
WAVE	Wireless access for vehicular environments
WLAN	Wireless local area network

CHAPTER 1: INTRODUCTION

Demand for high bit rate is pushing the researchers in the field of wireless communication systems to think about short range communications instead of long range communication in some specific applications. Mobile ad hoc network/vehicular ad hoc network (MANET/VANET) is a short range communication paradigm that can meet the requirement of high bit rate. However, MANET/VANET will not be realizable if the packet loss due to mobility related problems are not solved. MANET/VANET is different from traditional local area network (LAN) or wireless LAN (WLAN) with their multi-hop networking in which the mobile hosts are routers and form dynamic connections with other hosts in their radio ranges (i.e. transmission ranges). These multi-hop topologies present many unavoidable challenges in the physical layer, medium access control (MAC) layer and network layer. Some of these potential challenges are dynamically changing routes, and continuously varying radio characteristics between communicating hosts. These challenges are amplified while considering multi-hop ad hoc networks where data transport is not constrained to a single wireless network link. It is found that the throughput of a multiple link route in an ad hoc network decreases drastically if the nodes are mobile. That is why it is a significant challenge to improve the performances of a MANET by overcoming problems at different communication layers. My research goal is to investigate problems in packet communication in MANET which evolves from mobility and mitigate these problems in order to improve the network throughput and latency.

1.1 Contributions

The contributions in this thesis can be broadly divided into three parts e.g. network layer contribution, MAC layer contribution and network-MAC cross-layer design contribution.

- Since mobility is inevitable in MANETs, link failures are very common and cause packet loss as a consequence of inconsistent routes. Most of the on-demand routing protocols use route maintenance procedure to detect broken links and reroute packets. This increases packet delay. Packet losses and delays get worse when mobility increases. In order to mitigate unnecessary packet loss, a novel mobility algorithm is proposed in which the approximate route life time (RLT) is estimated, and this route is utilized only this amount time to limit the packet loss. The packet transmission is stopped after the route life time, then route discovery or alternative routes are used for the remaining packets.
- Packet collision in wireless communication systems is one of the most important sources of delay and network inefficiency which affect safety critical information dissemination applications the most in the network [1]. The cooperative vehicle safety system (CVSS) is designed to serve a safety critical application of the dedicated short range communication (DSRC) technology proposed for vehicular ad hoc networking [2]. DSRC, as part of wireless access vehicular environment (WAVE), uses IEEE 802.11p as the MAC protocol [3][4][5]. Since IEEE 802.11p's MAC is based on the distributed coordination function (DCF), it does not solve mobility related problems like mobile hidden station (MHS) [6], asymmetric/unequal radio link (ARL/URL) [7], and blocking problems like neighborhood capture (NC) [8]. This thesis contains a detailed discussion of these problems and their effects in MANET/VANET in Chapter 2. The MHS problem is unique in mobile networks and occurs if a mobile station enters in a collision free zone of any ongoing communication and disturbs this communication with its transmission. A novel MAC protocol named extended reservation Aloha (ERA) is proposed to address these problems. ERA is based on the modification of reservation Aloha (R-Aloha). ERA fully

solves the HS and NC problems, and partially solves the MHS and ARL problems. This is why, a second MAC protocol, called extended sliding frame reservation Aloha (ESFRA), is proposed which uses the concept of ERA and sliding frame R-Aloha (SFRA). ESFRA is particularly designed to solve the MHS problem in a MANET by including relative locations of transmitting stations in the packet frame information header. In addition to the MHS problem, ESFRA simultaneously solves the hidden station (HS), exposed station (ES), neighborhood capture, and asymmetric radio link problems. These proposed protocols are explained in Chapter 4.

- According to the analyses in [10] and [11], the early CVSS solutions work well in low utilization cases (i.e. at low vehicle density). For crowded highways, the performance of a CVSS degrades significantly due to the DSRC channel congestion [2], [12]–[15]. The causes of this congestion is the dissemination of information by flooding, collisions due to hidden stations and mobile hidden stations, neighborhood capture problem, asymmetric radio link problem etc. So CVSS needs a robust and efficient information dissemination mechanism. Although flooding by broadcast is robust enough to disseminate redundant information, it requires more bandwidth and delay. This is why, it is necessary to design algorithms to reduce DSRC channel congestion and end-to-end delay by limiting high volume of broadcast messages and by solving the above mentioned problems (i.e. HS, MHS, NC, ARL etc.). In this thesis, I have presented a network-MAC cross-layer protocol named cross-layer extended sliding frame reservation Aloha (CESFRA) which is based on the concept of ESFRA [16]. CESFRA is a controlled broadcast mechanism where all the stations maintain their slot reservation by a sliding frame (SF) mechanism, and broadcast their packets in their pre-reserved slots in every frame. CESFRA manages the channel accessing, disseminates the safety critical information in a novel approach which solves MHS, ARL and NC problems and eliminates the congestion behavior of flooding approach. CESFRA also confirms end-to-end low deterministic delay, and increases robustness by redundancy of information. The DSRC/WAVE systems are designed to support various services of different transmission ranges (i.e. 1000 meter emergency vehicle alert messaging, 300 meter collision avoidance messaging etc.) which create the ARL problem and thus more collisions. CESFRA can disseminate any information up to the third hop without any routing. For example, the DSRC/WAVE systems uses 1000 meter transmission ranges for the emergency vehicle alert message whereas CESFRA disseminates it up to 900 meter using 300 meter transmission range. In case of the collision avoidance alert messaging, the DSRC/WAVE systems take care of only one hop (i.e. 300 meter) whereas CESFRA manages to disseminate the information up to the third hop (i.e. 900 meter). The analysis shows that CESFRA decreases the frame transmission delay, increases the throughput, and reduces the collision probabilities compared to IEEE 802.11 and SFRA. The improved performance is obtained at the expense of the synchronization compared to IEEE 802.11, but there is virtually no extra cost compared to SFRA.

1.2 Thesis Organization

The thesis is organized as follows. All the network layer and MAC layer problems addressed in this thesis are explained in Chapter 2. How the network layer of a MANET is affected by mobility is briefly explained in the beginning of this chapter. Then the NC problem in the MAC layer is explained. The MHS problem is explained using both MANET and VANET scenario. The effect of the ARL problem in DSRC/WAVE systems is characterized. The research methodology of this work is presented at the end of this chapter. Chapter 3 contains the discussion on the related literatures reviewed for this research. Some related network layer mobility algorithms are briefly discussed. Because most of the researches in this thesis are in the MAC layer, different types related MAC protocols are discussed with respect to MANET and DSRC/WAVE systems. The MAC protocols are categorized as contention based and reservation based, and the reservation based protocols are considered best suited to address the most of the MAC problems. The proposed solutions are explained in Chapter 4. A mobility algorithm in the network layer of a MANET is proposed to reduce packet loss due to link failure. A reservation based MAC protocol is proposed to address the MAC problems and is modified to make it suitable for safety critical information dissemination. Detailed analyses of the proposed solutions are presented in Chapter 5. The proposed network-layer mobility algorithm is evaluated in NS-2. The proposed MAC protocols as well as some other related contention based and reservation based existing MAC protocols are evaluated using Combinatory theory, Markov analysis and OMNeT++. The thesis is concluded in Chapter 6.

CHAPTER 2: PROBLEM DEFINITION AND RESEARCH METHODOLOGY

2.1 Link Failure Due to Mobility in MANET and Its Severity

One of the major challenges in MANETs is link failures due to mobility [17]. Because nodes in a MANET act as routers for any ongoing packet communication and have limited transmission ranges, the communication links are broken, and packets are lost. This problem is amplified when a route constitutes several such links. If any of those links fails, the route breaks, which initiates series of undesirable events and outcomes. If how long a link is operational can be predicted, the routing protocol can use this to limit its use, which in turn reduce the packet loss in this link. It is assumed that every link remains connected for a limited time, called link life time (LLT), and a route has a limited life, called RLT. The RLT depends on the LLTs of the links that are constructed, that is why RTL can be taken as the lowest LLT in the route. When degree of mobility increases, LLTs and eventually RLTs decrease. That contributes to increase in packet losses and low throughputs in a MANET.

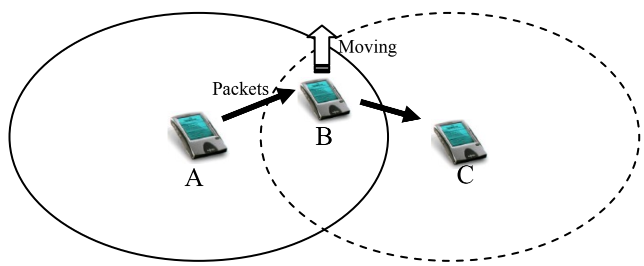


Figure 2-1: Link breaking due to mobility in an ongoing communication.

For example, Station A is communicating with C using B as a router and B is moving towards any direction as shown in Figure 2-1. If B moves outside the detection range of A or C or both, the communication link between A and C will be disconnected and some packets of the ongoing communication will be lost. A route or path from source to destination may constitute of several such links. The link which will remain connected for the lowest amount of time in a route will determine the life of that route termed as RLT. As degree of mobility in any topology increases, the RLT decreases and so the packet loss increases due the frequent breakage of links. Mobility is an inevitable property of a MANET. So, there is no other way but search good approaches for dealing mobility challenges like the packet loss.

2.2 Neighborhood Capture Problem in MANET

The neighborhood capture problem is observed in a multiple mobile station environment where one station is deprived of accessing the channel captured by its neighbor stations for long time. Let us try to understand the neighborhood capture problem with the scenario in Figure 2-2. This scenario contains six nodes where Node B is in the transmission range of both A and C which are out of the transmission ranges of each other (i.e. the distance between A and C is greater than the transmission range). Moreover E is in the transmission range of A; D is in the transmission range of C; and F is in the transmission range of B.

Figure 2-3 illustrates a data transmission scenario. Suppose B has accessed the channel first and is transmitting data to F as shown in Figure 2-3. After the end of B's transmission, the channel is free for any of the nodes A, B and C. Now C has data to transmit, and it starts to transmit. At this moment, B does not have a chance to transmit as it is in the transmission range of C, but A is free to use the channel as it is out of transmission range of C. Node A starts transmission as it has data to transmit now. At this moment, the situation of the channel is, if B wants to access the channel, B must have to wait until both A and C release the channel simultaneously, which is almost uncertain because of the variable length of the data transmissions of A and C or asynchronous transmissions. So B is severely affected by its neighbors A and C, and this phenomenon is called "Neighborhood Capture".

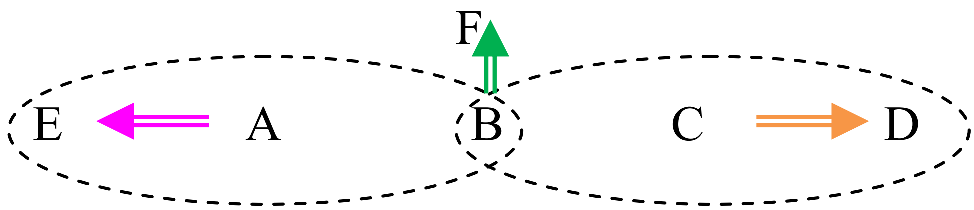


Figure 2-2: Neighborhood capture scenario.

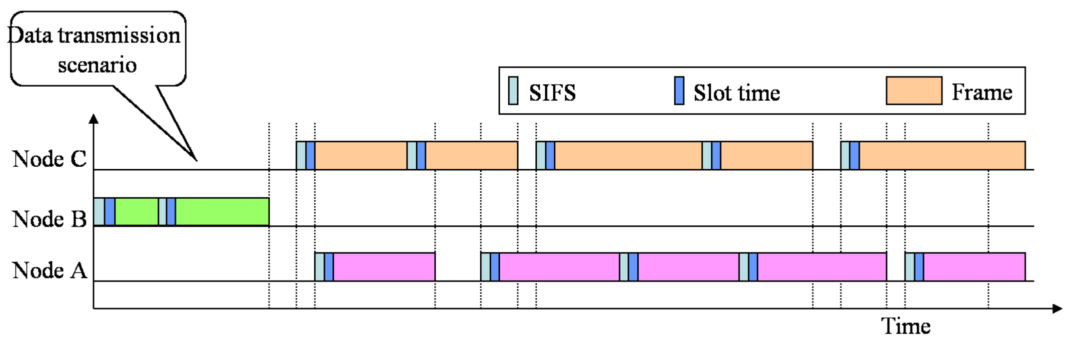
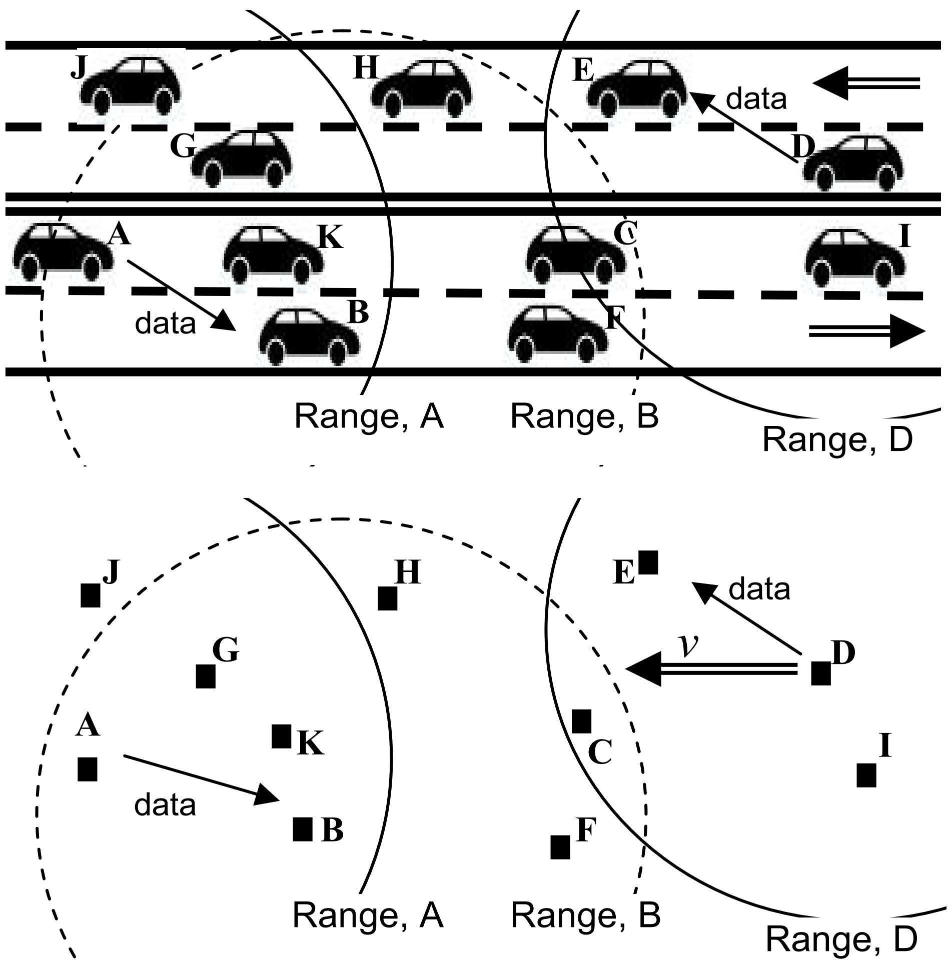


Figure 2-3: Data transmission scenario at the time of neighborhood capture.

2.3 Mobile Hidden Station Problem in MANET or DSRC/WAVE Systems

Mobility is ever increasing in today's lifestyle, and wireless networks have to accommodate user mobility in the network. MANETs, mesh networks and VANETs are a few network types that will eventually be deployed along with cellular communication systems. Relatively high mobility in those networks creates unique problems. One such problem is the mobile hidden station problem. Figure 2-4(a) illustrates the MHS problem in a VANET scenario, and Figure 2-4(b) illustrates the problem in a MANET scenario. In these illustrations, Station D is communicating with Station E, and Station A is communicating with Station B. When Station D moves into the interference range of Station B, D disturbs Station A's communication with B with its transmission. Stations like D in the illustrated scenarios are called mobile hidden stations, because they are hidden first, but disturb receptions of the other transmissions when their transmissions interfere with the reception of others. MHSs can affect up to twenty five percent of the nodes in a VANET employed in a highway scenario, if a two-way highway accommodates equally probably distributed vehicle traffic, because stations moving in the opposite direction of the traffic will become MHSs to the stations on the other side of the highway [2]. Analysis provided in this thesis shows that MHSs severely degrade network performance. That is why a MAC protocol must have to solve the MHS problem in mobile networks. ESFRA is proposed to address the MHS problem. It significantly reduces performance degradations due to mobility. HS is solved using request to send (RTS) and clear to send (CTS) messages in the IEEE 802.11 MAC. However, RTS/CTS introduce the ES problem. ESFRA solves these four problems, namely MHS, NC, HS, and ES simultaneously to facilitate improved utilization of scarce mobile network resources. The proposed protocol is based on the sliding frame reservation Aloha (SFRA) [18][19]. Messages in the sliding frame mechanism of SFRA transfer control information up to the second hop neighbors [18]-[20], which is sufficient to solve HS and ES problems. This SFRA control information transfer mechanism alone does not solve the MHS problem because mobile stations at third hops away from the ongoing communication are not informed.



(a) A mobile hidden station scenario in VANET. (b) A mobile hidden station scenario in MANET.

Figure 2-4: Mobile hidden station scenario in VANET and MANET.

2.4 Asymmetric Radio Link Problem in MANET/ VANET and Its Severity

2.4.1 Asymmetric Radio Link Problem in MANET

Asymmetric links are common in wireless networks [7][9][21]. Figure 2-5 illustrates a scenario to explain ARLs in a mobile network where Station A is sending packets to B, and C and D are HSs because of ARLs. Hardware limitations, power saving protocols, shadowing effects, dynamic spectrum managements causes ARLs in a wireless networks [7][9][21]. Let us consider using IEEE 802.11 MAC protocol in Figure 2-5, hence B's CTS packet is heard by hidden Station C. As hidden, Station D is out of the transmission range of B, it does not hear B's CTS, and so D can transmit packets and these packets can collide with A's transmitted packets at B. Thus, HS problem due to the ARL is not addressed by IEEE 802.11 MAC.

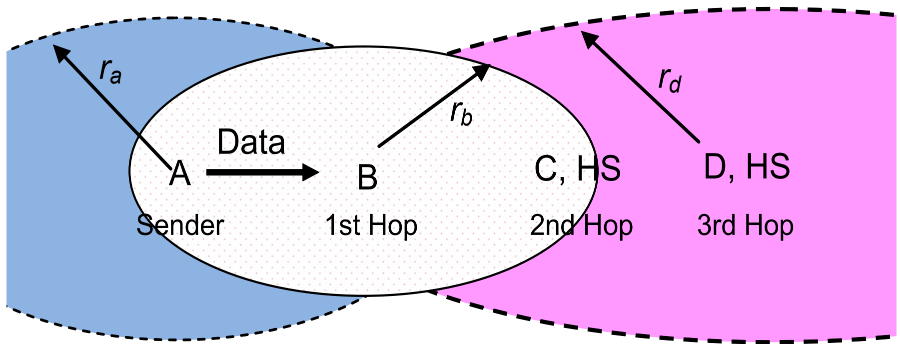


Figure 2-5: HS in an asymmetric radio link MANET scenario.

2.4.2 Asymmetric Radio Link Problem in DSRC/WAVE Systems

The DSRC/WAVE systems use different transmission ranges and different data rates for different types of messages as shown in Figure 2-6 [22].

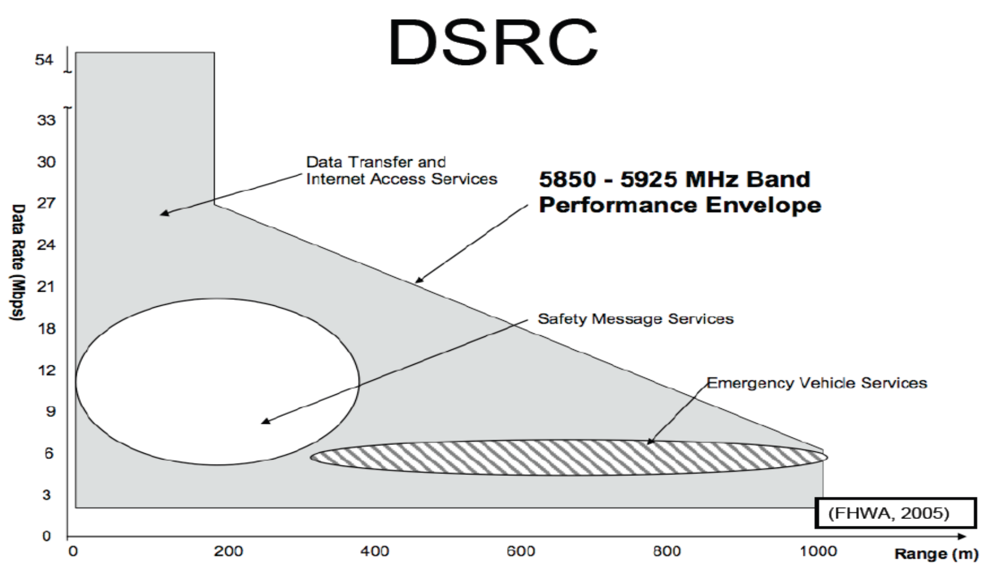


Figure 2-6: DSRC multichannel communication ranges (Copied from [22]).

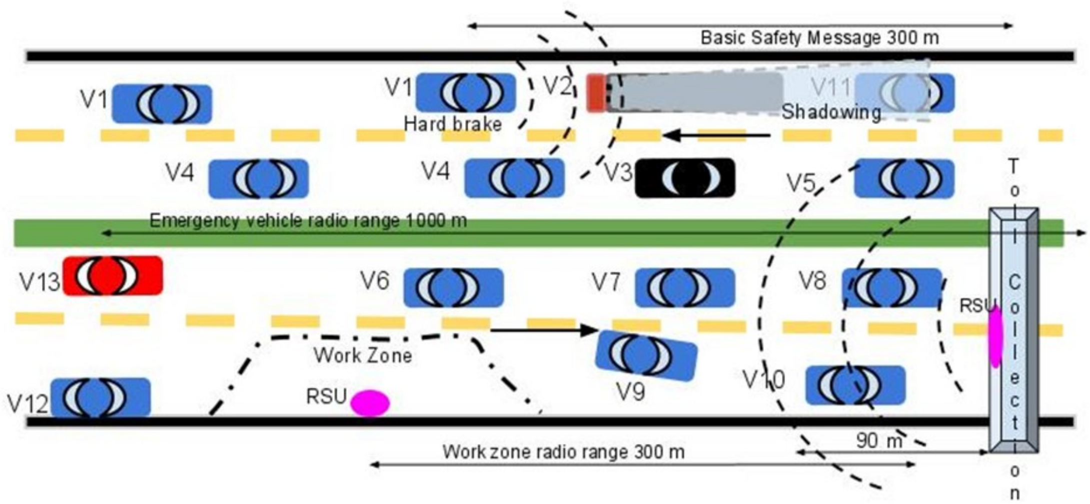


Figure 2-7: HSs in an unequal/asymmetric link VANET scenario.

Let us consider a VANET scenario in Figure 2-7 where the radio links are maintained according to the DSRC/WAVE systems. In DSRC systems, an ARL arises when the transmission power of a service channel is varied to support different services with different transmission ranges. For example toll collection service uses about 10 to 90 meters (m) transmission range where as road condition warning services, like work zone warning uses 90 to 300 m transmission range. Similarly, the control channel is used for emergency vehicle warning with transmission range up to 1000 m, and the basic safety message transmissions with transmission range of 300 m. In addition to transmission range differences, ARL can occur with shadowing such as experienced by the car behind the truck in Figure 2-7. In order to address the ARL problem, the control information is required to be distributed up to the 3rd hop nodes as illustrated in Figure 2-5. It is difficult to meet this requirement by an unsynchronized and distributed MAC protocol such as IEEE 802.11 MAC. Some of the synchronized and reservation-based MAC protocols can increase the performance of the network with problems related ARL such as SFRA in [18][19]. However SFRA does not solve ARL problem but reduced its impact in the performance. That is why I have investigated ESFRA proposed in [16] which provides a complete solution to problems caused by ARLs. Mainly, ESFRA passes the control information up to the 3rd hop, thus it eliminates problems related to ARL.

2.5 Research Contributions and Methodology

2.5.1 Research Contributions

- Short-term Objective Based Contributions:

- Investigated packet losses due to link failures in MANETs/VANETS.
- Developed algorithms to reduce packet losses due to link failures in MANETs/VANETS.
- Characterized and investigated the neighborhood capture problem in MANETs/VANETS.
- Characterized and investigated packet losses due to MHSs in MANETs/VANETS.
- Developed a new MAC algorithm to solve the MHS and neighborhood capture problems in MANETs/VANETS.
- Investigated the new MAC algorithm with discrete time Markov chain (DTMC).
- Investigated the new MAC algorithm in OMNeT++.
- Investigated the cross-layer (i.e. network and MAC layer) behavior of the new MAC algorithm.

- Major Contributions:

- Developed a MAC layer scheme which addresses all the problems mentioned in Section 2.2.

- Developed a cross-layer scheme which constitutes the developed MAC algorithm as well as a network layer control on packet losses due to link failures.

2.5.2 Research Methodology

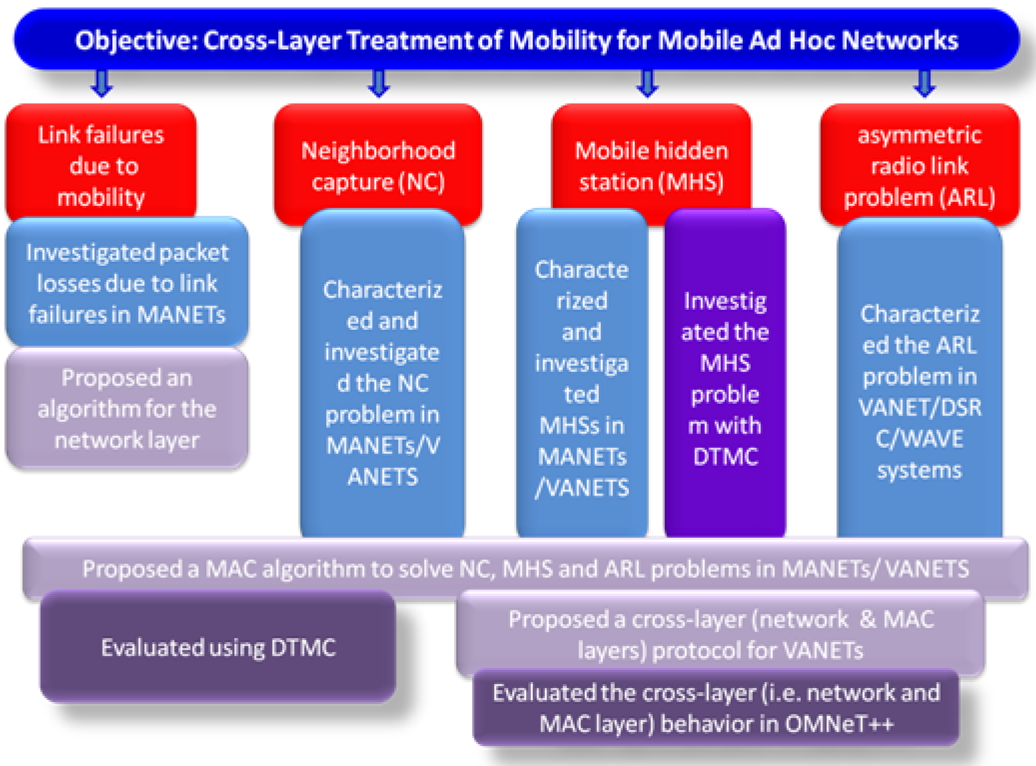


Figure 2-8: Research methodology and accomplishments.

Step 1: Mobility causes packet losses in MANETS. I studied literatures to identify the factors affecting the packet communication when stations are mobile. I found two significant factors: **link failures**, and **mobile hidden stations**. Some other factors have drawn my attention along with mobility problems. Those are **neighborhood capture** and **asymmetric/unequal radio link** problems. All these four problems (See Figure 2-8) are investigated and solved throughout my research work.

Step 2: In this step, a mobility algorithm is developed in the network layer to reduce packet losses due to link failure [23]. The mobility algorithm is investigated in NS-2, and it was implemented with dynamic source routing (DSR) protocol. The algorithm is applicable to any on-demand routing protocol.

Step 3: The adverse effects of the neighborhood capture problem and mobile hidden station problems in the MAC layer of MANETs are characterized. The NC problem is analyzed using Combinatory theory [8]. The MHS problem is analyzed using both Combinatory theory [24] as well as DTMC [6]. The hidden station problem in a VANET is investigated in [25].

Step 4: I did research to devise a novel approach to treat the NC, MHS, ARL and other problems in the MAC layer. First, I developed a new MAC protocol named ERA and analyzed with respect to the NC and MHS problems [24]. Another protocol, SFRA is also analyzed with respect to the MHS problem [26]. Then I used the concept of ERA into SFRA, and developed ESFRA. ESFRA is analyzed using DTMC with respect to the NC and MHS problems [16]. ESFRA is also analyzed with respect to the ARL problem in [21] and compared with other MAC schemes in [27].

Step 5: CESFRA is proposed which is based on ESFRA. CESFRA MAC is evaluated in OMNeT++ with respect to the MHS and ARL problems [28]. The behavior of IEEE 802.11p broadcast and CESFRA MAC is analyzed using DTMC with respect to the criteria set in the DSRC/WAVE systems [28].

Step 6: Completion of the thesis.

The research problems are identified and the methodology for this research is defined in this chapter. There are some issues which are not addressed in this research, and which should be solved. Those are time synchronization among the mobile stations, privacy issues and security issues in the vehicular communication. Some related literatures are discussed in the next chapter.

CHAPTER 3: RELATED WORK

The research work in this thesis is related to the network and MAC layers. So the literatures reviewed throughout this research work are divided into two sub-sections based on the related communication layers.

3.1 Review of the Impact of Mobility in the Network Layer

A part of this thesis is related to the impact of mobility in the network layer of wireless ad hoc networks. So, some of the mobility related papers are discussed in this sub-section. A model to compute an upper bound for the maximum network size in a MANET is proposed in [29]. According to the analysis presented in [29], a route would die due to mobility after a certain number of hops. A protocol is proposed in [30] for managing MANETs. In this protocol, a small subset of the network nodes, called backbone network, is selected based on the nodes' statuses. The protocol in [30] operates in two phases: first the "most suitable" nodes are selected to serve as backbone nodes, and then a backbone network is formed by using these nodes. Topology dynamics is investigated in [31] based on the smooth mobility model. The smooth model generates smooth and microscopic nodal movements, and maintains a uniform spatial node distribution. The model predicts link existence based on the present distance between a pair of nodes and their relative speeds. The analysis in [31] reveals that the expected link life time decreases exponentially with increasing mobility. Results presented in [31] were not tested in any protocol. A mobility assessment on-demand (MAOD) routing protocol is proposed to select a stable route in order to enhance system throughput and performance [17]. MAOD is an on-demand routing protocol similar to dynamic source routing (DSR) protocol [32]. The difference between MAOD and DSR is in the path selection method. As MAOD takes the mobility of the hosts into consideration, it selects a more stable route than DSR. In MAOD, an error count parameter is used to measure mobility of a host. However, the error count method has problems in judging the mobility of the nodes because it does not indicate which node is mobile, the node itself or the nodes around it. Even if a node is static, it needs to increase its error count when its neighbors are mobile. A new measure of mobility in which each node estimates at regular time intervals its relative mobility with respect to its neighbors is proposed in [33]. A multicast scheme, on-demand multicast routing protocol (ODMRP) [34], has been recently proposed for MANETs. ODMRP is a reactive (on-demand) protocol that delivers packets to a destination in a mesh topology using scoped flooding of data. ODMRP proposes a method to predict the link expiration time, which is based on a more realistic propagation model, and uses received signal strength indication (RSSI). But, instantaneous RSSI values may not be reliable for fading channels since its fluctuations vary significantly in short time and distances.

3.2 Review of the Behavior of Some Related MAC Protocols

Existing MAC protocols for MANETs can be broadly divided into two categories e.g. distributed and reservation based protocols. IEEE 802.11 and its modified versions (e.g. 802.11e, 802.11p) are distributed protocols [35] and successfully deal with HS and ES problems with their RTS/CTS mechanism [36][37]. When IEEE 802.11 MAC is used in MANETs, Station V4 stays outside of the interference range of Station V7, as shown in Figure 3-1, and as soon as it moves in the interference range of V7, its packets will collide with V6's packets to V7 because Station V4 did not receive any CTS, and it was unaware of V6's transmission to V7.

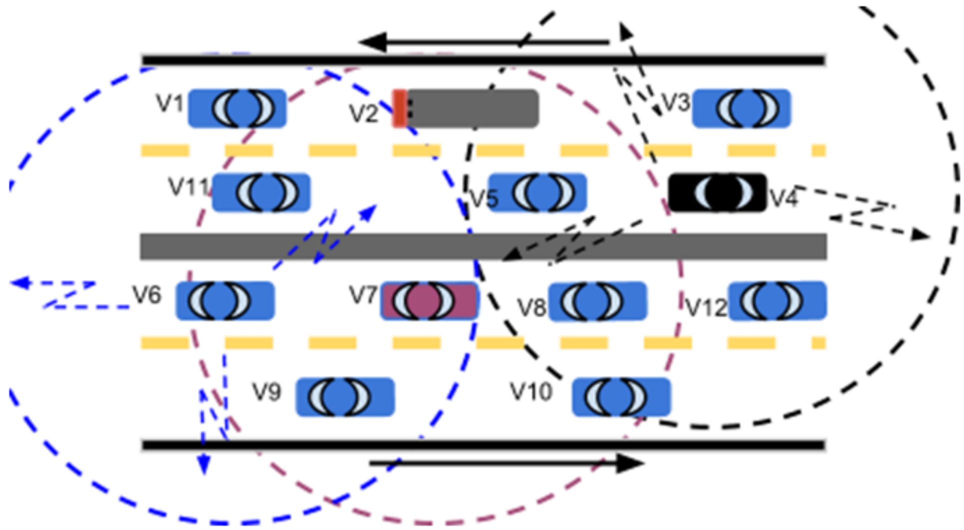


Figure 3-1: Mobile hidden station scenario.

IEEE 802.11p is the most recent draft standard which is used in wireless access in vehicular environment (WAVE) [38][4]. Since IEEE 802.11p's MAC is based on the distributed coordination function (DCF), which does not solve mobility related problems like MHS, or blocking problems like NC. Authors in [39] proposed an adaptive M-ary tree algorithm with priority broadcast (ATPB). This MAC scheme builds a tree that is assumed to be dynamic and adaptive, and prioritizes the stations according to their needs. ATPB is completely based on RTS/CTS, this is why it solves HS and ES problems, but cannot solve the MHS problem. Dual busy tone multiple access (DBTMA) is an asynchronous and distributed scheme, which was proposed in [40] and [41]. The total bandwidth is divided into three channels, one for the transmission of data, and the other two are for busy tones used to inform the neighbors of the sender and the receiver. Consequently, DBTMA creates a collision free zone up to a maximum of two hops from the sender just like IEEE 802.11. Thus it fails to address the NC and MHS problems. Interleaved MAC protocol is a distributed scheme which uses two frequency channels, one for RTS and DATA, and the other for CTS and acknowledgement (ACK) [42]. Thus it solves HS and ES problems, and decreases the blocking probability due to the NC problem, but it does not completely solve the MHS problem. Global channel release (GCR) is a synchronized distributed scheme in which all stations release the channel at the same time, and all contending stations have an equal chance to access the channel [43]. This requires slotting of the channel into super-frames and synchronization of all stations; the resulting protocol would be a slotted CSMA/CA [43]. That is why GCR solves the NC problem, and also solves HS and ES problems by creating a collision free zone similar to IEEE 802.11, but does not address the MHS problem. Synchronous reservation based scheme (i.e. ERA [8], SFRA [44] etc.) solves the access related HS, ES and NC problems, and reduces collisions due to MHSs. All the MAC schemes mentioned above solve HS and ES problems, only the synchronous MAC schemes mentioned above solve the NC problem. Synchronized reservation based MAC schemes mentioned above reduces collisions due to MHSs but do not fully solve the MHS problem. So synchronous reservation based schemes work better to address the MAC problems.

Although the wireless medium is fundamentally different from the wired one, the conventional layered architecture fails in wireless networking [45]. The authors in [45] offer cross layer design (CLD) as an alternative for wireless networks. They showed that some unintended cross-layer interactions may create undesirable consequences. For example, principle of rate-adaptive MAC protocol [46] is to use higher transmission rates in a good quality channel. In this case, the higher rates are maintained by changing different modulation schemes. The authors in [45] showed that such schemes can have undesirable consequences for the higher layers. When rate-adaptive MAC is used with minimum hop routing, the performances get worse as minimum hop routing uses longer hops for which the signal strength is lower, and thus the rate-adaptive MAC will always choose low rates. The authors in [47], [48]and [49] discussed repetition based protocols for DSRC MAC. Those are asynchronous p-persistent repetition (APR) [47], asynchronous fixed repetition (AFR) [47], synchronous p-persistent repetition (SPR) [48], synchronous fixed repetition (SFR) [48], AFR by adding a carrier sensing (CS) mechanism (AFR-CS) [48], and positive orthogonal codes (POC) [49]. All these protocols are designed without considering the effect of hidden stations and mobile hidden stations which are inherent in vehicular ad hoc communications. The analysis in [48] shows that SPR and SFR perform better than asynchronous protocols (i.e. APR and AFR), and SFR performs better than SPR. The authors in [49] showed that POC works better than SFR. The authors in [50] analyzed the performances of SPR, SFR and POC protocols considering the effect of hidden stations, which shows that these protocols do not meet the minimum requirements for safety critical information dissemination. The authors proposed SFRA in [19], which is developed by CarTALK/FleetNet IVC system in Europe [51], one of the most promising protocols for distributed wireless networks [44]. The author in [52] analyzed the suitability of an R-Aloha based protocol for inter-vehicle communication in multi-hop networks. The dynamic behavior of SFRA is analyzed in [19], [44] and [53]. The authors in [26] analyzed the performance of SFRA considering the adverse effects of MHS and NC problems along with HS and ES problems. This analysis shows that SFRA reduces collisions due to MHSs, but it does not solve the MHS problem in MANETs/VANETs. I have quantitatively measured the behavior of SFRA with ARL problem in [21]. The analysis in [21] shows that the probability of collision increases with the increment of the number of transmitting stations while using SFRA as a MAC protocol. The probability of successful channel accessing is also severely affected by HSs due to ARLs. IEEE 802.11p is the most recent draft standard used in WAVE [12][13]. Since IEEE 802.11p's MAC is based on the distributed coordination function, which does not solve mobility related problems like MHS, ARL and NC problem according to the analysis in [1], [6] and [8] respectively. Moreover, a quantitative approach presented in [54] shows that the broadcast performance of IEEE 802.11p is inefficient for short safety messaging in DSRC systems.

That is why, I proposed to design CESFRA which addresses all the MAC problems and makes safety critical information dissemination in DSRC/ WAVE systems routing less, robust, fast and reliable, and which is compared with some of the related literatures. The detail discussion on the proposed work is presented in the next sub-section.

CHAPTER 4: PROPOSED WORK

The research throughout this thesis is associated to network layer, MAC layer and network-MAC cross layer. So, the proposed work is divided into three sub-sections based on the layer basis contributions.

4.1 Proposed Work in the Network Layer

4.1.1 A Mobility Algorithm to Reduce Packet Loss

The duration of connectivity between two nodes is unlimited for static ad hoc networks whereas it changes with mobility in MANETs. Link failures are inevitable if the nodes are mobile, and get more severe when the mobility of nodes increases. Link failures increase packet loss considerably. In order to reduce the packet loss due to link failures, mobility needs to be integrated in routing protocols. This integration needs to be independent of routing protocols to have an effective solution. However, on-demand routing protocols (i.e. DSR [32], ad hoc on-demand distance vector (AODV) [55]) are considered as the candidate to apply the developed mobility algorithm. The algorithm is based on an efficient use of the duration of connectivity of two neighboring nodes in a route. This duration is called LLT throughout this thesis.

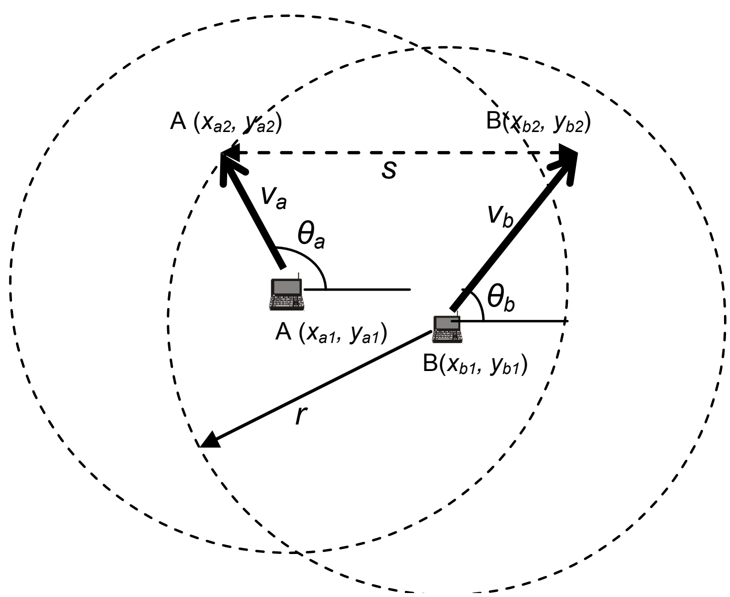


Figure 4-1: A scenario for calculating LLT.

4.1.1.1 Calculation of Link Life Time

In [34], a method to calculate LLT is proposed. This method is utilized for the calculation of LLT in this mobility algorithm. The calculation is briefly presented here for the clarity of the discussions to be made later. Figure 4-1 shows two mobile nodes A and B with their radio ranges, r. The current locations of A and B are $A(x_{a1},y_{a1})$ and $B(x_{b1},y_{b1})$, respectively. A and B are moving with velocities v_a and v_b, and angles

θ_a and θ_b, respectively. Their future locations are $A(x_{a2},y_{a2})$ and $B(x_{b2},y_{b2})$ after some time duration, t. It is assumed that nodes A and B are not changing directions within this time duration, t.

If all the information related to their current locations, such as v_a, θ_a, v_b, θ_b, x_{a1}, y_{a1}, x_{b1} and y_{b1} are known, their future locations can be calculated using the provided information from known values by the following two functions.

$$A(x_{a2},y_{a2}) = f(t, v_a, \theta_a, x_{a1}, y_{a1}). \tag{4.1.1}$$

$$B(x_{b2},y_{b2}) = f(t, v_b, \theta_b, x_{b1}, y_{b1}). \tag{4.1.2}$$

If the distance between A and B after time t is s, then

$$s^2 = (x_{a2} - x_{b2})^2 + (y_{a2} - y_{b2})^2. \tag{4.1.3}$$

A and B will be able to communicate with each other as long as they will remain within their transmission ranges, r. So, t = LLT if $s \leq r$. After solving Equation (4.1.3) with $s \leq r$ and considering t = LLT, I get

$$\mathbf{LLT} = \frac{-(ab+cd)+\sqrt{(a^2+c^2)r^2-(ad-bc)^2}}{a^2+c^2}, \tag{4.1.4}$$

where, $a = v_a \cos\theta_a - v_b \cos\theta_b$, $b = x_{a1} - x_{b1}$, $c = v_a \sin\theta_a - v_b \sin\theta_b$, and $d = y_{a1} - y_{b1}$.

4.1.1.2 Calculation of Adaptive Link Life Time

The transmission range is an important factor in MANETs. Normally the radio ranges of mobile nodes in any network are considered equal. The authors of [56] calculated LLT considering that the radio range of each mobile node in an ad hoc network is equal. In reality, the transmission ranges of mobile nodes in any wireless network might be unequal for variety of reasons. Asymmetric/unequal radio links are common in wireless networks for a variety of physical, logical, operational, and legal considerations [7][21]. The transmission range of a node might be limited by the capabilities of the hardware or by power limitations. A node might need to limit its transmission power to avoid interference with a licensed user of the spectrum, or because of dynamic spectrum management considerations. In military applications, considerations of stealth might require some nodes to reduce their transmission power. If this holds true, the link will expire before the calculated LLT according to the scenario shown in Figure 4-2. Because, according to the procedure of LLT calculation in the previous sub-section, Node B will calculate the LLT using r_b considering that its partner A has the same transmission power. Unfortunately, it will give B an LLT value larger than the real value. Implementation of this wrong LLT value will produce unexpected results and this necessitates a modification in LLT calculation.

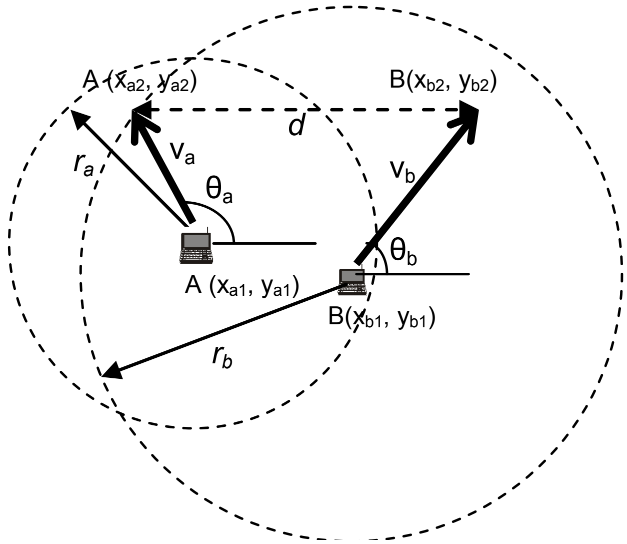


Figure 4-2: A scenario for calculating ALLT for asymmetric radio links in a MANET.

In this work, the modified LLT is calculated using the smaller of the two radio ranges as the future distance (i.e. *d*) between the two mobile nodes. This modified LLT is termed as adaptive LLT (ALLT) throughout this document as it is adaptive to unequal radio ranges of the mobile nodes in any wireless network. I have applied the following algorithm along with the LLT calculation in the previous sub-section to calculate ALLT.

Let,

r_a = f (A's transmit power)

r_b = f (B's transmit power)

If ($r_b < r_a$) {

ALLT = f (LLT calculated with r_b)

else if ($r_a < r_b$)

ALLT = f (LLT calculated with r_a)

else

ALLT = f (LLT calculated with $r_a = r_b = r$)

}

4.1.1.3 Mobility Algorithm

The algorithm has been designed to treat mobility related problems in wireless networks. The size of a wireless network is significantly affected by the mobility of nodes [29]. As mobility increases, LLT between nodes decreases. This causes the routes to break quickly, and the packet losses due to the route breakages. All of those impacts negatively affect the network parameters such as packet delivery ratio, delay and throughput. The proposed algorithm solves the mobility related routing problems and comprises the following 4 steps.

Step 1: Source estimates a minimum threshold link life time: In any on-demand routing protocol like DSR, routes that are used for sending data packets are discovered based on some requirements (i.e., routing metrics). In the proposed mobility algorithm, the source uses a minimum threshold link life time (TLLT) to discover more stable links and routes. The source estimates TLLT based on the nature of mobility (i.e. urban area or highway). Unlike highway, random mobility scenario prevails in urban area. Statistically more than twenty percent of the routes in a random mobility scenario die out within few seconds [57]. Routes in a highway mobility scenario are more stable compared to routes in a random mobility scenario. Thus, TLLT can be set higher for highways compared to a random mobility scenario. TLLT in a random mobility scenario can be set higher for low speeds compared to high speeds.

Step 2: Using TLLT in route discovery process to detect unstable routes: In case of any on-demand routing protocol, whenever the source has a packet to send, it searches a route in the route cache. If there is no route available in the cache, the node sends a route discovery packet to a desired destination. In the proposed algorithm, the source sends TLLT in the route discovery packet.

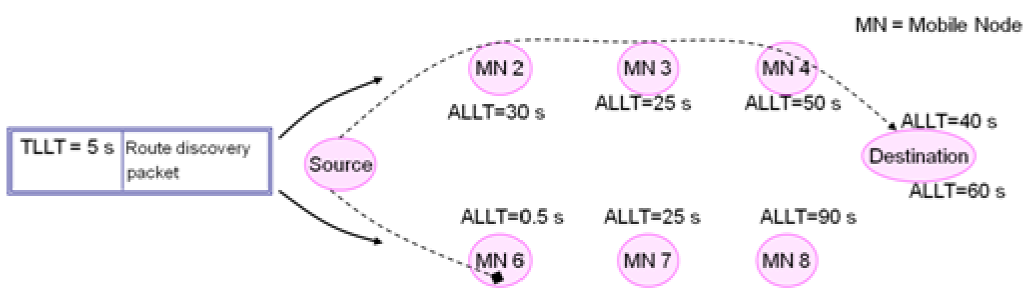


Figure 4-3: Discarding unstable routes.

Each node along the path toward the destination calculates its own LLT with the previous node, and compares the calculated LLT with the TLLT in the packet. If the calculated LLT is greater than the TLLT of the packet, this node becomes a part of the route. Otherwise, it is not included in the route. Figure 4-3 illustrates a simple scenario where the source sends a route discovery packet with TLLT = 5 seconds. MN 2 and MN 4 agree to be part of the route comparing their LLTs. But, MN 6 refrains becoming part of the route since its LLT is lower than the TLLT. The described provision prevents discovering routes that have less stable links.

Step 3: Determination of route life time: How long a route exists (i.e. RLT) is an important criterion for the proposed algorithm. An RLT is defined as the duration of the liveliness of any route. All the nodes in any route have their own LLTs, and the node with the lowest LLT has higher probability of breaking the route. So, the lowest LLT in any route is RLT. The scenario given in Figure 4-3 illustrates that, and MN 2's LLT (i.e. 30 seconds) is taken as RLT. According to the proposed algorithm, the source sends the route discovery packet with a large number in its RLT field (e.g., RLT = 99999 seconds.). If any node is a part of the route, it compares its LLT with the RLT in the route discovery packet. If the LLT is less than the RLT, it replaces the RLT field in the discovery packet with its own LLT. Otherwise, it forwards the route discovery packet without changing the RLT field. After getting the route reply packet, the source calculates the net RLT, RLT_{net}, which is the difference between RLT of the packet and the time it took the route reply packet to arrive to the source, t_{route}. Then, RLT_{net} is given by

$$RLT_{net} = RLT - t_{route}. \tag{4.1.5}$$

The source stores the RLT_{net}, and the t_{route} in the route cache. t_{route} is considered average latency between source and destination, which will be used to calculate how many packets are supposed to be successfully transferred from source to destination.

Step 4: Algorithm for reducing packet loss due to mobility using RLT: The route discovery process with mobility assisted routing is explained in Step 3. Whenever there is a packet to send, the source finds a route from the route cache, and sends an estimated number of packets that the respective route is able to deliver before breaking. Latency between source and destination, t_{route}, is important as well. That is needed to estimate the number of packets that can be sent by the source to the destination. Let us assume N_{est} be the estimated number of packets to be sent through that route, and given by

$$N_{est} = RLT_{net}/ t_{route} . \tag{4.1.6}$$

According to Equation (4.1.6), the selected route remains alive during RLT_{net}, and within this RLT_{net}, the source will be able to send approximately N_{est} number of packets. If the source sends more than N_{est} packets, the additional packets have higher probability of getting lost due to the broken route. After finding N_{est}, the packets are sent in order. If there are more packets to be sent, the source finds an alternative route from the route cache, and repeats the process for this route by calculating its N_{est}. If there is no route available in the route cache, the source starts the route discovery process. Figure 4-4 provides the flowchart of the algorithm.

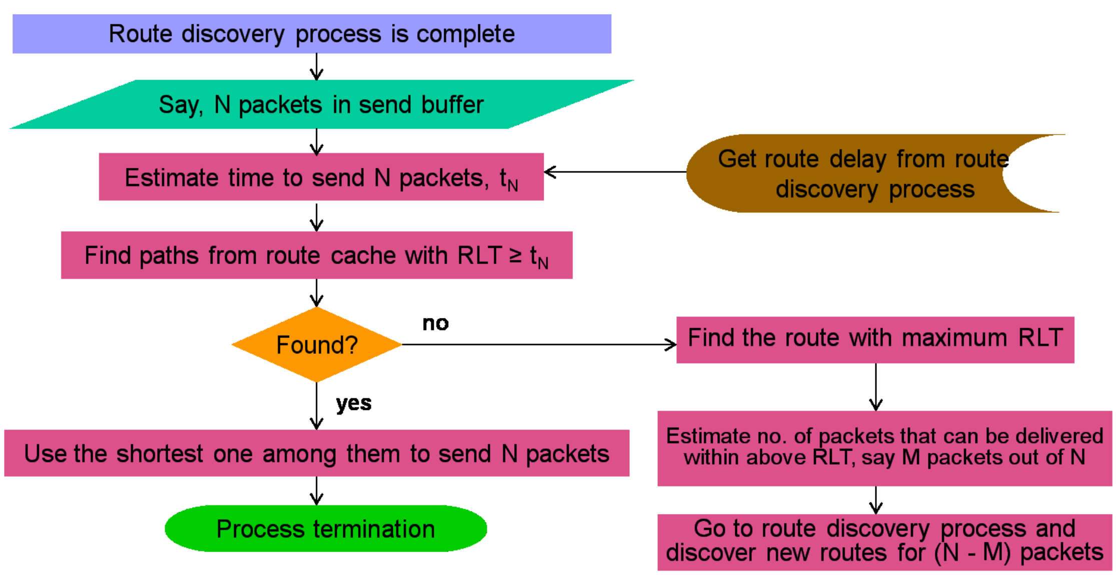


Figure 4-4: Flowchart for mobility assisted routing.

4.1.1.4 System Model and Implementation

MANETs with 10, 20 and 30 nodes are considered for testing the proposed algorithm. Each node in this network is considered to be equipped with global positioning system (GPS) (or any other positioning service) which is capable of providing the current location, direction of movement, as well as the current velocity of the mobile node. Packet losses occur in two ways (i.e. due to link failures and due to collisions [58]), and the emphasis here is given to reduce packet losses due to link failures. I have created two routes from source to destination that can be broken and reconnected continuously. These scenarios were tested with Network Simulator version 2.33 (NS-2) [59] in SuSE linux. According to the implementation, each node is using an omni-directional antenna with a height of 1.5 meters. Two ray ground reflection propagation model is chosen for radio propagation, and the path loss factor is four. The nodes are sharing the same channel for the packet transmission, and IEEE 802.11 [60] is used as the multiple access technique. Constant bit rate (CBR) traffic is used as the traffic mode at the source, and it is producing 512 byte data packets. User datagram protocol (UDP) is used as a transport layer protocol. Loss monitor is used at the destinations to monitor and measure the observed parameters at the end of each transmission. The simulations were run 200 seconds each time. I have used DSR as a routing layer protocol, and DSR is combined with the proposed mobility algorithm. I have considered four modifications in the route discovery phase of DSR protocol. First, whenever a node receives a route discovery packet, it calculates LLT with its previous node. Second, each route discovery packet contains a TLLT value assigned by the source. Any node that receives a route discovery packet compares its calculated LLT with the TLLT in the packet, and drops the packet if the LLT is less than the TLLT. Third, the RLT of the discovered route is estimated with the minimum of the LLT values of the nodes along the route. Fourth, the destination calculates latency of each route, and sends this to the source through route reply packet. In data transmission phase, the source finds the shortest route according to the principle of DSR. Then, the source estimates the approximate number of packets to be sent using the RLT and latency of the corresponding route. That provision reduces packet loss due to link failures. I call this implementation “DSR with LLT”.

The proposed mobility algorithm in this sub-section will be analyzed in Sub-section 5.1. The next sub-section contains the proposed algorithms in the MAC layer of a MANET/VANET.

4.2 Proposed Work in the MAC Layer

Some MAC problems (i.e. HS, ES, MHS, NC, ARL etc.) in the MAC layer of ad hoc networks can be solved with R-Aloha based MACs. Transmission of special type of control messages through the frames gives a very good opportunity to save the radio channel from neighborhood capture. The proposed MAC protocols are discussed in this sub-section. Before going to the proposed MAC protocols, a brief view of the Reservation Aloha is presented in the next sub-section.

4.2.1 A View of Reservation ALOHA

Reservation Aloha (R-Aloha) is a packet access scheme based on time division multiplexing (TDM). In this protocol, certain packet slots are assigned with priority, and it is possible for users to reserve slots of a frame for the transmission of packets. Each time slot is long enough for the transmission of a packet of data. The duration of a frame is assumed to be greater than the maximum channel propagation delay in the broadcast network [61]. Slots can be permanently reserved or can be reserved on request. According to the principle of R-Aloha each user is aware of the usage status of time slot one frame ago. The network operates without any central control, but requires each user to obey the same set of rules for transmitting packets into time slots depending upon what happened in the previous frame. A time slot in the previous frame may be:

Unused, which means that it was empty (previously not used) or instantly vacant due to a collision among several packets. Used, which means that exactly one packet was transmitted in a slot and the packet was successfully received (it is assumed that the channel is error-free except for collisions).

The transmission rules in R-Aloha are as follows-

- If slot m had a successful transmission by user X in the previous frame, slot m is not available to anyone except user X in the current frame. Slot m is said to be reserved by user X. Note that user X has exclusive access to slot m as long as it continues to transmit a packet into in every frame.
- Those slots in the last frame, which were unused, are available for contention by all users according to the adaptive algorithm.

4.2.2 The Proposed MAC Protocol: Extended R-Aloha (ERA)

The traditional R-Aloha is not enough to remove the access related problems (i.e. HS, ES and NC problems) in ad hoc networks. I have modified the R-Aloha, called extended reservation Aloha, to use it with ad hoc networks. The basic modifications that I have made to the traditional R-Aloha are described in the following three steps.

1) Two stations under a communication are using the same slot in different frames one after another. They are establishing a bi-directional TDD connection sharing the same slot in the consecutive frames.
2) Any of the two stations is using one slot and reserving the same slot in the subsequent frame which will be used by the other station.
3) Any of the two stations using one slot in the current frame and reserving the same slot in the next two subsequent frames.

As shown in Figure 4-5, station A is transmitting to station B. Station C is out of detection range of A. So C may be a HS to A during ongoing communication. Again station D is inside the detection range of A. So D may be an ES to A during ongoing communication. ERA has been explained using the scenario in Figure 4-5, described how it solves the HS and ES problems, provided that the above three modifications are applied here.

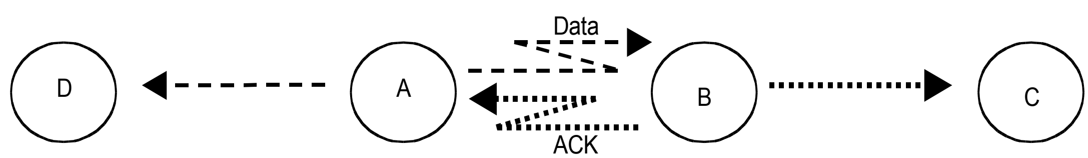


Figure 4-5: ERA to hidden station and exposed station.

(1) If A and B use different slots in the same frame or different frames it is difficult to inform C about A's reservation and D about B's reservation. If A and B use the same slot in every frame one after another as shown in Figure 4-6, this problem is solved, and thus C knows about A's reservation from B's reservation.

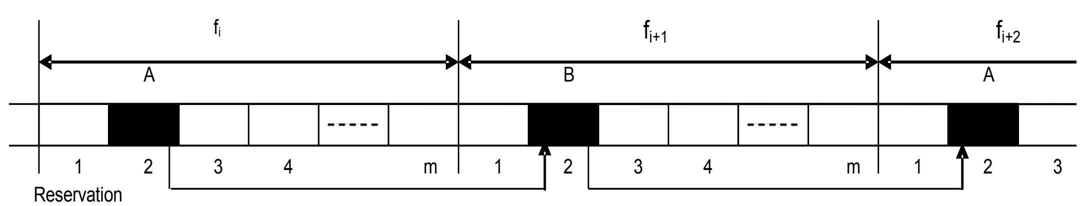


Figure 4-6: Reservation scenario in R-Aloha.

(2) Station A has seized slot 2 of frame i for the communication with station B. It is using this slot as well as reserving slot 2 of frame i+1 as shown in Figure 4-6 (follow the unidirectional arrow). According to modification (1) station B is bound to use the same slot (i.e. slot 2) in the frame i+1. So B is using slot 2 of frame i+1 and according to modification (2), it is reserving slot 2 of frame i+2.

According to modification (2), after A's transmission using slot 2 of frame i, D knows about A's reservation of slot 2 in frame i+1. When B sends acknowledgement to A using slot 2 of frame i+1, C works as ES, and there is no problem from D (HS to B). After B's transmission using slot 2 of frame i+1, C knows about B's reservation of slot 2 in frame i+2. When A sends data to B using slot 2 of frame i+2, D works as ES, and there is no problem from C (HS to A). If the transmission continues in this way, then it confirms the solution of the HS problem, but not of the ES problem.

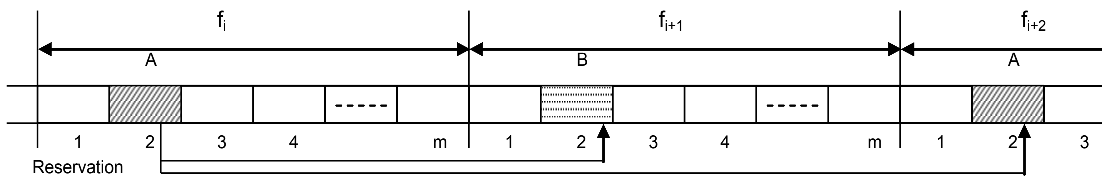


Figure 4-7: Extended reservation scenario in ERA.

(3) Station A has seized slot 2 of frame i for the communication with Station B. It is using this slot and reserving slot 2 of frame i+1 as well as slot 2 of frame i+2 at the same time as shown in Figure 4-7 (See the unidirectional arrow). All stations follow the same rules.

According to modification (3), after A's transmission using slot 2 of frame i, D knows about A's reservation of slot 2 in frames i+1 and i+2. When B sends acknowledgement to A using slot 2 of frame i+1, C works as ES and no problem from D (HS to B). After B's transmission using slot 2 of frame i+1, C knows about B's reservation of slot 2 in frames i+2 and i+3. When A sends data to B using slot 2 of frame i+2, there is no problem from D (ES to A) and C (HS to A). If the transmission continues in this way it confirms the solution of both HS and ES problems.

4.2.3 The Proposed MAC Protocol: Extended Sliding Frame R-Aloha (ESFRA)

ESFRA is based on SFRA, and accordingly SFRA will be briefly presented here in order to understand some reasons why ESFRA is superior for mobility.

4.2.3.1 Sliding Frame Reservation-Aloha

In SFRA protocol [18], the channel time is divided into time slots, which are grouped to form a frame. Each frame is assumed to contain N slots. The basic mechanism of the protocol is described in the following steps:

- At start up, each station acquires one slot as its basic channel (BC) to transmit its packet, which contains a payload and a field called frame information (FI).
- Stations reserve BCs as long as they are active. SFRA uses the FI field to distribute stations' view of the statuses of the slots, whether the slots are busy or free. Each station records the statuses of the previous N slots, which is called a sliding frame (SF).
- At each slot, the received FI is used to update the statuses of the following N slots of the SF. In this way, a station knows the communication statuses of the stations up to 2 hops away. So, the stations positioned at least three hops apart can reuse the busy slots. With this, SFRA solves hidden and exposed station problems.
- Slots are automatically released when stations are turned off or exit the transmission ranges of all other active stations in the frame.

Figure 4-8 is provided to illustrate how SFRA works using a scenario. There are 4 stations in this scenario; the stations are labeled as S_1, S_2, S_3, and S_4; where S_1 is sending data to S_2, and S_4 is moving towards S_3. Busy slots are labeled as "B", and free slots are labeled as "FR".

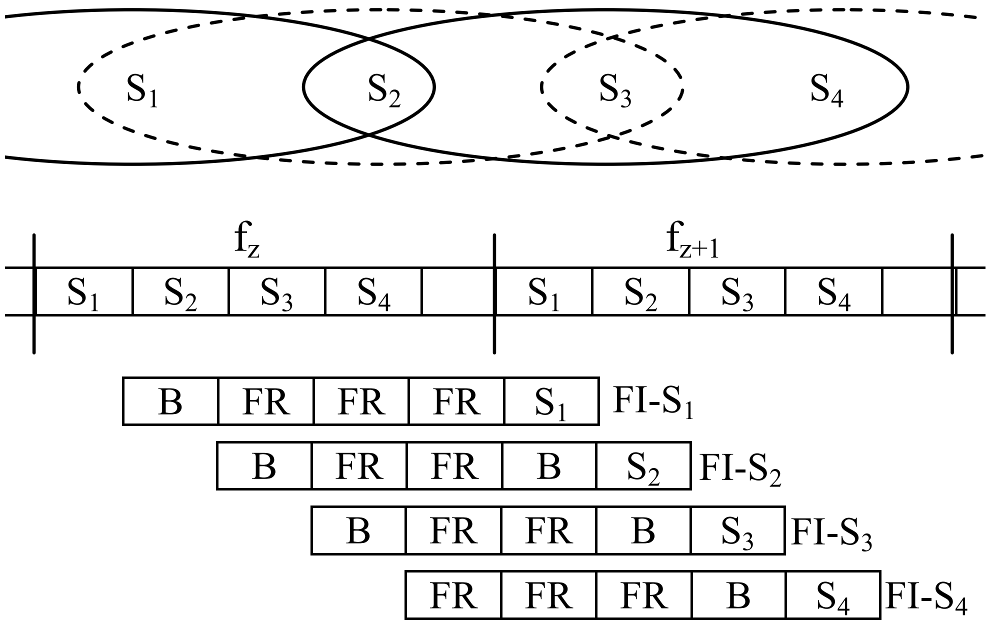


Figure 4-8: Sliding frame scenario of SFRA.

Let us assume that all stations are using only their BCs for both FI and data transmissions. All the stations, S_1, S_2, S_3, and S_4, have reserved their BCs. S_1's FI informs all the stations around S_1 about the slots that are used by S_1. Similarly, S_2's FI informs all the stations around S_2 about the slots that are used by S_2. Thus, S_2's FI contains the statuses of the slots reserved by both S_1 and S_2. Also, as S_3 receives S_2's FI, it knows the slots used by S_1 and S_2. As a result S_3, which is a hidden station to S_1, avoids using those slots for its transmission, which prevents the collisions at S_2.

According to SFRA, S_4 knows the slots used by Stations S_2 and S_3 from FI of S_3 but it does not know about S_1's reservation. While transmitting to any other station, S_4 can move to the transmission range of S_2, which causes collisions at S_2.

4.2.3.2 Principles of Extended Sliding Frame R-Aloha

ESFRA is based on SFRA, and designed to solve the MHS problem. However, the FIs in ESFRA uniquely inform relative positions of the stations in addition to the status of a slot. With this modification, stations learn if a busy slot belongs to an immediate neighboring station or to a station which is 2 or 3 hops away. Another modification introduced with ESFRA is the access to the free slot, where the free slots are open to contention to allow the mobile stations access to the medium. There can be collisions in this contention period but the collisions are contained in this free slot, and do not happen in the busy slots. With these modifications, ESFRA handles the mobility much better than SFRA. Properties of ESFRA are described as follows:

(i) The contending station senses the idle slot for a random small amount of time while reserving a free slot. This is done by using a small back-off timer. The contending station with a lower value in its back-off timer has the priority to reserve a free slot first. If there is a collision, it resets the back-off timer again. This back-off procedure is applied only at the time of reserving a free slot at the start of a communication.

(ii) In order to avoid unnecessary losses at the receiver at the start of a data transmission, it is necessary to know whether the expected receiver is free or not. Whenever a station has a packet to send to any other station, it sends RTS to the expected receiver to know its status. If the expected receiver is free to communicate, it sends CTS to the sender. The sender transmits the packets using the reserved slots in every frame. RTS/CTS handshaking is done only at the starting of any new transmission. By using ESFRA the sender infers that the receiver is aware of subsequent reserved slots.

(iii) In a low traffic network, any station can reserve extra available slots for more data transmission.

(iv) The MHS problem will be solved if the MHSs are managed to be aware of any communication in advance. According to SFRA, a station knows the communication statuses of the stations up to two hops apart. ESFRA manages to distribute the status of a slot assignment to three hops by organizing the FIs with a new scheme. The FIs in ESFRA contain reservation information of three consecutive stations, and the stations located at least 4 hops away are able to reuse the slots. The FI in ESFRA contains the status information of a slot that specifies whether this slot contains a successfully received packet, which is labeled as BUSY-1 slot, BUSY-2 slot, or FREE slot. The busy slots are recognized as reserved, and the free slots are recognized as available. If a station discovers that any station is using a slot for transmission, it does not use this slot, and the slot is recorded as BUSY-1 in its own FI. If a station discovers any slot with status BUSY-1 in any of its received FIs, it does not use this slot, and the slot is recorded as BUSY-2 in its own FI. If a station discovers any slot with status BUSY-2 in any of its received FIs, it does not use this slot, and the slot is recorded as FREE in its own FI. The free slots are always recorded as FREE.

Figure 4-9 illustrates how ESFRA works using a scenario. S_1 is sending data to S_2, and S_4 is moving towards S_3. In this scenario, S_3 is a *hidden station* to S_1, S_5 is *exposed station* to S_1, and S_4 is *mobile hidden station* to S_1. In Figure 4-9, "BUSY-1" is labeled as "B1", "BUSY-2" is labeled as "B2", and "FREE" is labeled as "FR".

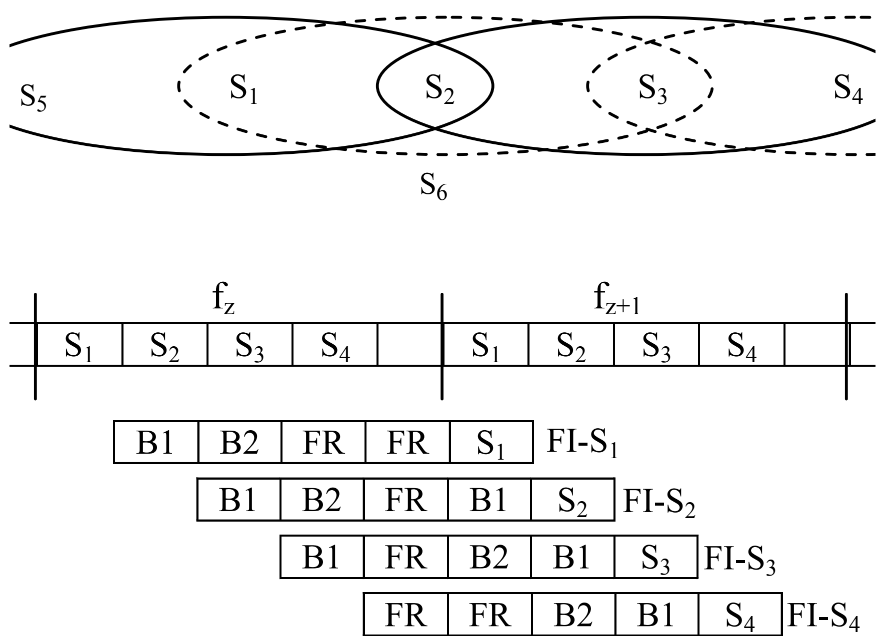


Figure 4-9: Sliding frame scenario of ESFRA.

Let, stations S_1, S_2, S_3 and S_4 have reserved the slots 1, 2, 3 and 4 in a frame respectively as their BCs, and they are using only their BCs both for FI and data transmission. The FIs in Figure 4-9 show that S_2 is recording S_1's reservation as BUSY-1, S_3's reservation as BUSY-1, and S_4's reservation as BUSY-2. Similarly, S_3 is recording S_1's reservation as BUSY-2, S_2's reservation as BUSY-1, and S_4's reservation as BUSY-1. Thus, the modified sliding frame mechanism works for distributing slot status up to three hops, and offers smooth slot switching. The mobile hidden station gets enough time to switch to an idle slot before becoming a second hop neighbor if it finds its reserved slot busy as a third hop neighbor.

Sub-section 5.2.3 will provide how ESFRA deals with HS, ES, NC and MHS problems, and a detailed analysis by using Markov modeling. The network-MAC cross-layer algorithm is explained in the next sub-section.

4.3 The Proposed Network-MAC Cross-Layer Algorithm

Communication systems are divided into layers for reducing complexity in processing and regulating information to be transmitted in wired or wireless networks. Wireless networks characteristics are quite different from wired networks in some of the cases which create new challenges. Researchers are applying different techniques to solve those challenges. For some specific scenario, researchers are using the dependencies and interactions between adjacent layers which brings the concept of cross-layer design (CLD) [1]. The channel conditions from PHY and MAC can be used in the network, transport and application layer for designing the optimized algorithms specially in case of unstable channel conditions (i.e. mobility, limited bandwidth, power constraints, dynamic network topologies etc.). The algorithm proposed in this section makes the MAC layer useful for disseminating network layer information.

4.3.1 The Proposed Cross-Layer Based Algorithm

4.3.1.1 Construction of Cross-Layer Extended Sliding Frame R-Aloha

The cross-layer extended sliding frame reservation Aloha is based on the modification of the principles of ESFRA, and it is designed to support safety critical information dissemination in VANETs. So, CESFRA is an vehicular communication application specific version of ESFRA. ESFRA is basically designed for medium access control in ad hoc networks. According to the mechanism of ESFRA [16], any mobile station situated at most three hops away from the sender is aware of the respective communication. This property of ESFRA can be used for routing among the mobile stations situated up to three hops away. So, ESFRA can be used as a cross-layer (i.e. both MAC and network layers) protocol for the applications where three hops routing is sufficient, such as collision avoidance in VANET, advance association between vehicles and road side units (RSUs), communication between two RSUs in WAVE etc.. Normally, ESFRA uses a small field called FI, which contains the statuses of the previous slots of the sliding frame for passing medium access controlling information to the next neighbors. The FI in ESFRA requires some enhancements to make it cross-layer information (CI).

The structure of a CI is shown in Figure 4-11. Each CI contains two types of information e.g. FI which carries control information (i.e. FREE, BUSY-1, BUSY-2 etc.), and upper-layer information (UI) which needs to be transmitted (i.e. basic safety message (BSM) and other high and low priority information) to next hop or multi-hops. BSM is transmitted by each vehicle every 100 milliseconds [62]. Other information to be transmitted (i.e. traffic information, weather information, emergency vehicle alert, lane change alert, blind spot alert, collision avoidance alert etc.), information hop number (IHN), packet ID etc. are considered as upper layer information. Information hop number means how many hops an information must be forwarded. For example, lane change alert and blind spot alert are one hop information because these messages are to be transmitted only one hop, whereas emergency vehicle alert and collision avoidance alert are multiple hop information. The construction of CIs in CESFRA is as follows:

1 If a station has packets to send it searches a free slot from its FI, reserves it for a specified number of frames, and release it at the end. If it does not have enough packets, it releases the channel as soon as its queue is empty. For a network where number of communicating stations is very low compared to the number of slots in a frame, the stations are allowed to reserve more than one slot in a frame. The stations increase their slot reservation one by one keeping at least one slot free. If a new station appears, it reserves that free slot. As soon as the other stations observe this reservation, they release one slot each from their excess reservations. This rule is followed while arriving or departing a station to/from the collision domain.
2 If a station listens to any other station using a slot for a transmission, it does not use that slot. That slot is marked as BUSY-1 in its own CI. If it is a one hop message (i.e. IHN equals to one), it is dropped after reading the information otherwise the UI of the owner of that slot is copied to its own CI.
3 If a station finds any slot with status BUSY-1 in any of the received CIs, it does not use that slot. That slot is marked as BUSY-2 in its own CI. If it is a one hop message, it is dropped after reading the information otherwise the UI of the owner of that slot is copied to its own CI.
4 If a station finds any slot with status BUSY-2 in all the received CIs, it does not use that slot. That slot is marked as FREE in its own CI. If it is a one hop message, it is dropped after reading the information otherwise the UI of the owner of that slot is copied to its own CI.and transmitted by it.
5 Free slots are always marked as FREE.

This slot reservation mechanism is explained with state diagram in the next sub-section.

4.3.1.2 State Diagram of Slot Status in CESFRA

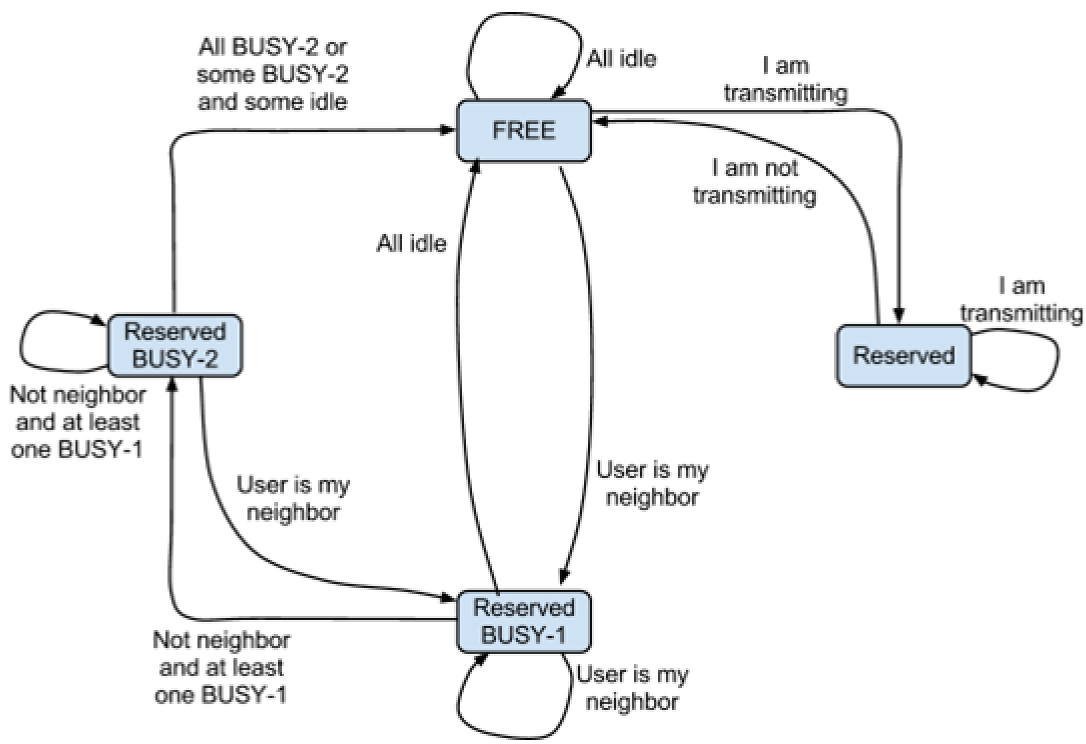


Figure 4-10: The state diagram of the status of a slot in CESFRA.

CESFRA eliminates the collisions using the FI part of the CI. FI contains the statuses of the slots of the sliding frame. Every slot in an FI must be in any of the four statuses as illustrated in Figure 4-10. Those are idle, reserved, reserved BUSY-1 and reserved BUSY-2. The slot status in a current FI is reported based on the statuses of the corresponding slot in the received FIs. The future state of a slot may be FREE in three ways e.g. (1) if it is reported as BUSY-2 in some of the received FIs while others are idle or BUSY-2 in all the received FIs, (2) if it is reported idle in all the received FIs, or (3) if any station releases it. The slot state changes from FREE to Reserved if a station starts transmission using that slot. It reports this slot as reserved as long as it keeps on transmitting. Whenever it releases the slot, it changes its state to FREE. If a slot is used by a neighbor, it will always be reported as BUSY-1 in the current FI. If the user of a slot is not a neighbor and if the slot is reported as BUSY-1 in any of the received FIs, its state will be BUSY-2 in the current FI. In the next section, I will explain how FI is extended to CI, and how it is used for information dissemination.

4.3.1.3 Information Dissemination Mechanism with CESFRA

The BUSY-1 and BUSY-2 in CI passes the reservation information of any slot up to third hop without any routing support as discussed in the previous sub-section. A CI is a complete packet to transmit. Every CI contains a number of fields equal to the number of slots in a frame. Every field has two parts e.g. control information and UI. Slot statuses, slot numbers etc. are control information, and vehicle ID, BSMs, collision information etc. are UI. Any information included along with the control information will also pass up to three hops in VANET without any routing support. If RSUs are installed maximum three hops away from each other, neighboring RSUs will be able to communicate with each other using V2V communication. In other words, CESFRA can forwards safety critical information in a controlled broadcasting manner without any routing support. For one hop information forwarding, any station includes the one hop information into its own CI field and broadcasts the CI. The neighbors just read the information from the sender's CI and do not add it to their own CIs. For multi-hop information dissemination, the emergency message generating vehicle puts the message into its own CI along with a specified IHN. Every vehicle who receives this CI will copy in its own CI and transmit. The IHN in a slot is decreased by one along with the change of the status of the corresponding slot.

Figure 4-11 illustrates a collision avoidance scenario using CESFRA. It also shows the snapshots of CIs transmitted by vehicles. Vehicle a in the highway scenario in Figure 4-11 generates hard brake message to avoid collision, and this message should be reached at Vehicles b, c and d in advance. The frame constitutes of 10 slots, and each vehicle reserved one slot for transmitting its own CI. Here, every CI contains slot reservation information (i.e. slot number ($s1$, $s2$, etc.), vehicle ID (a, x, b, etc.), slot status (B1, B2, F)) and upper layer information (i.e. collision information and BSM). Vehicle a reserved slot 1 for transmitting a BSM. After a collision detection it included the collision information (i.e. coll info) into its CI (i.e. CI-a). Whenever Vehicle b receives CI-a, it changes a's slot reservation status to B1 in its own CI (i.e. CI-b), and copies the collision information. Vehicle b applies all other rules of Sub-section 4.3.1.1 to include slot statuses of all other received CIs into CI-b. After receiving CI-b, Vehicle c changes a's slot reservation status to B2 in its own CI (i.e. CI-c), and copies the collision information. Vehicle d gets the collision information from c's CI. Vehicle d deletes a's reservation in its own CI and does not use that slot. IHN is not used in this example communication scenario because the collision information is supposed to dissipate up to three hops.

The construction of CI and information dissemination mechanism of CESFRA is described in this section. Some critical VANET scenarios are designed in the Sub-section 5.3 to expose mobile hidden station and asymmetric radio link problems. The effectiveness of CESFRA with these problems is also described in Sub-section 5.3.

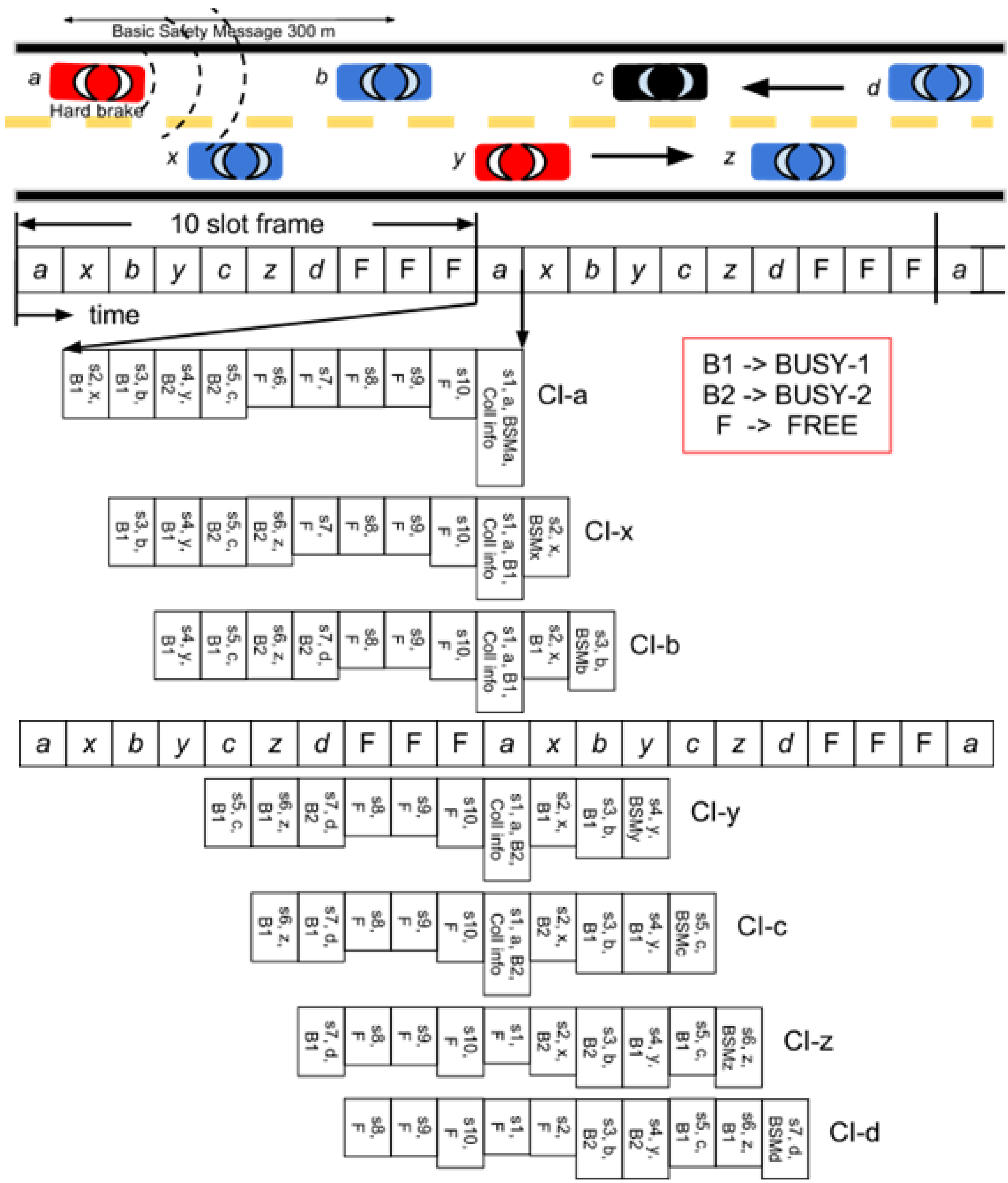


Figure 4-11: CI Structure for information dissemination.

CHAPTER 5: RESULTS AND ANALYSIS OF THE PROPOSED APPROACHES

All the proposed algorithms are analyzed in this chapter. The proposed mobility algorithm for the network layer is analyzed in Sub-section 5.1. All the MAC layer and network-MAC cross-layer analyses are included in Sub-section 5.2 and Sub-section 5.3 respectively.

5.1 Analysis of the Proposed Algorithm in the Network Layer

5.1.1 Investigation of the Mobility Algorithm on Dynamic Source Routing (DSR) Protocol

A mobility algorithm is proposed in Sub-section 4.1. This algorithm is applied to the DSR protocol for evaluating its performance. Three metrics are considered in measuring and comparing the performance of the proposed algorithm with existing solutions. Those metrics are packet delivery ratio, packet loss and average packet delay. Packet delivery ratio is the ratio between the number of received packets by the destination and the total number of packets sent by the source at the end of each simulation. Packet loss is defined by the total number of lost packets during the simulation. Average packet delay is defined as the span of time required by a packet to reach from source to destination. As I am dealing with the effect of mobility in an ad hoc network, I have chosen speed (i.e. meter/second) of the mobile nodes as a variable while measuring the performance of the protocols. I have compared my implementation with original DSR (i.e. "DSR with Error Count") and "DSR with Direction Tracking" [56]. Figure 5-1, 5–2 and 5–3 provide results of the simulations for a 10 node scenario. DSR has its own solution to broken routes, called route maintenance procedure, which deletes the route with a broken link from its cache. "DSR with Direction Tracking" is based on two considerations. First, searching for the shortest path, e.g. if LLT > 0, based on the number of hop-count from both primary and secondary caches.

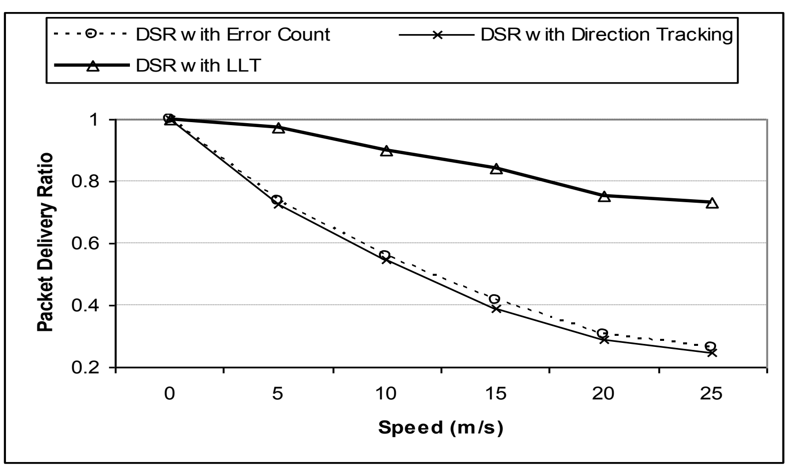


Figure 5-1: Packet delivery ratio versus speed.

Second, searching for a path with better LLT with the same minimum hop-count, and searching for a path with the best LLT value from both primary and secondary caches. Figure 5-1 shows that a significant improvement in packet delivery ratio can be obtained with "DSR with LLT". Packet delivery ratio is 46 percent more compared to other two schemes when the speed of the mobile nodes is about 25 meter/second. The bold line in Figure 5-1 shows that the packet delivery ratio (using DSR with LLT) is decreasing with increasing mobile speeds. This is due to the assumption made during LLT calculation that nodes are not changing directions within the duration of LLT. This causes some links to expire before the calculated LLT. That is why some packets are lost, which decreases the packet delivery ratio.

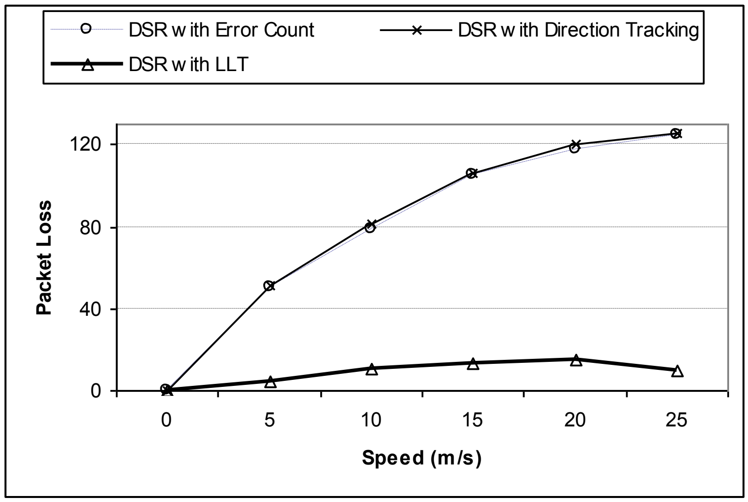


Figure 5-2: Packet loss versus speed.

Figure 5-2 shows that there is a significant reduction of packet loss with the use of the proposed algorithm in DSR. Packet loss is reduced by about 90 percent when the speed of the nodes is 25 meter/second. The average packet delay is determined by averaging the individual packet delay. Because same routes as in the traditional DSR is used in both schemes (i.e. "DSR with Error Count" and "DSR with LLT"), the average packet delay of these schemes should be same. This is evident in Figure 5-3 which shows average packet delay of schemes (i.e. "DSR with Error Count" and "DSR with LLT"). "DSR with Direction Tracking" and "DSR with Error Count" are using same routes with same strategy; this is why it is expected to have similar average packet delay.

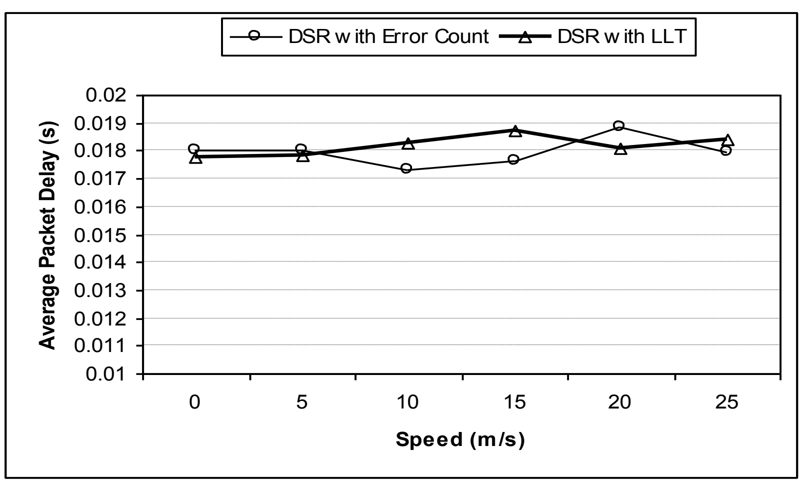


Figure 5-3: Average packet delay versus speed.

I have also simulated “DSR with LLT” in scenarios with different number of nodes (i.e., 10, 20 and 30 nodes) to see the impact of the size of a MANET on the mobility assisted algorithm. The comparative views between “DSR with LLT” and “DSR with Error Count” are shown in Figure 5-4, 5-5 and 5-6. The number of link failures is increasing with increasing of the number of nodes. So, the packet delivery ratio is decreasing in both “DSR with LLT” and “DSR with Error Count”, as illustrated in Figure 5-4.

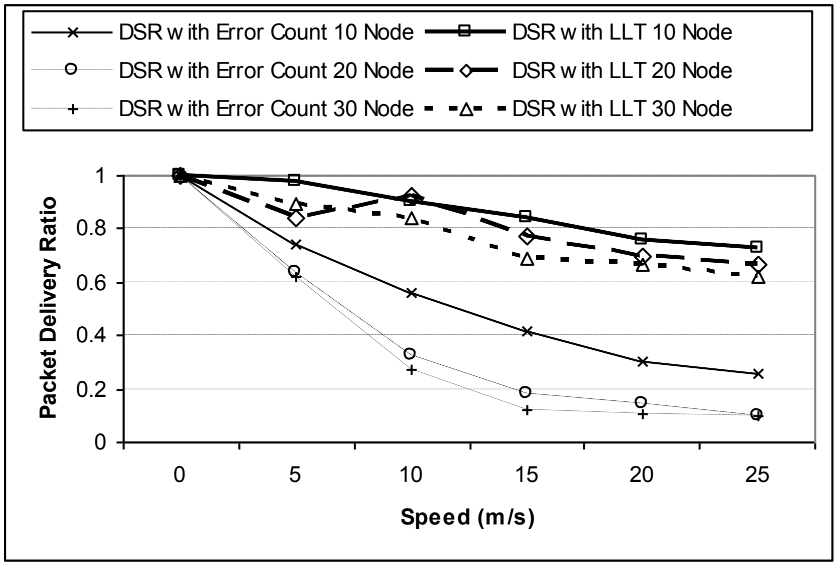


Figure 5-4: Effect of number of nodes on packet delivery ratio.

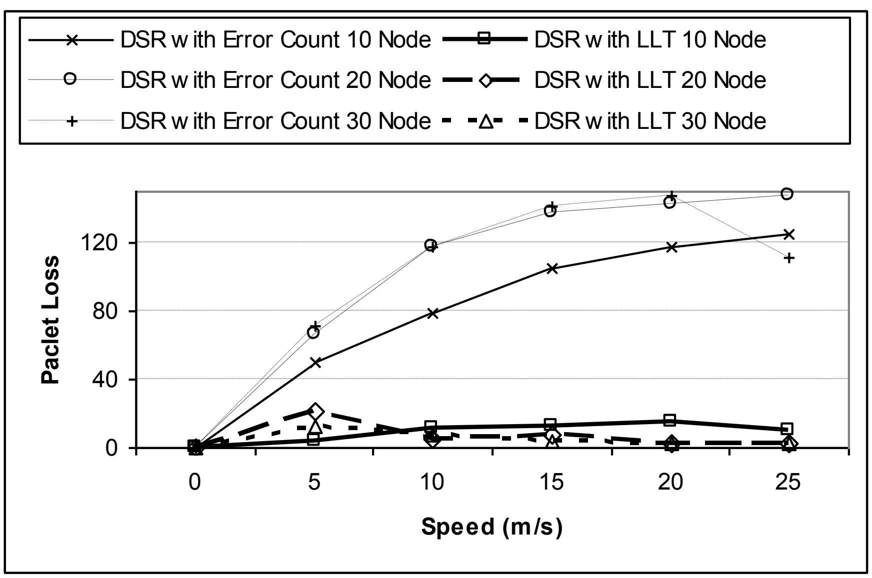


Figure 5-5: Effect of number of nodes on packet loss.

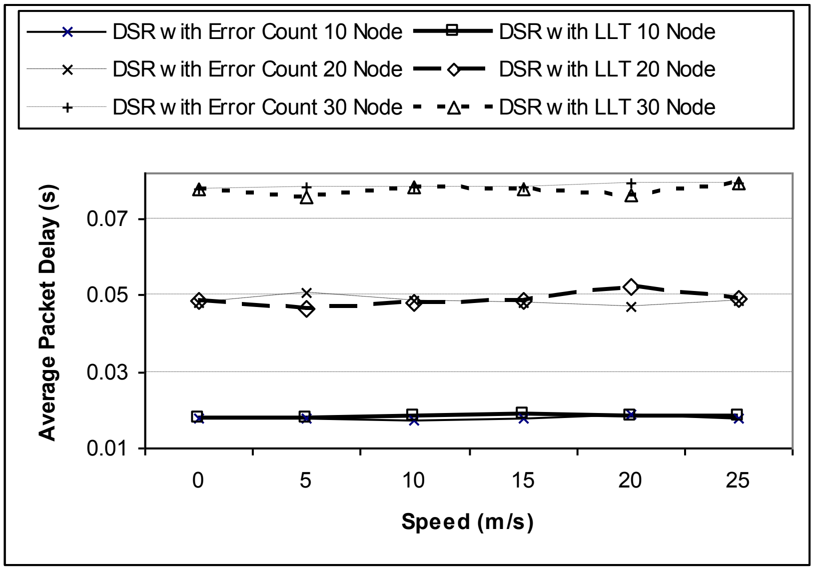


Figure 5-6: Effect of number of nodes on delay.

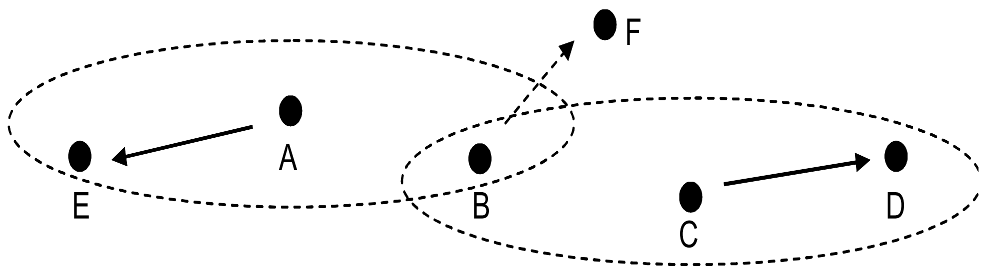
Figure 5-5 shows that more link failures are causing more packet losses in "DSR with Error Count". As my algorithm is sending the number of packets that the route can handle, packet loss is reduced by about 90 percent. Average packet delay is increasing with increasing of number of nodes for both protocols as average lengths of the routes are increasing, which was shown in Figure 5-6.

5.2 MAC Layer

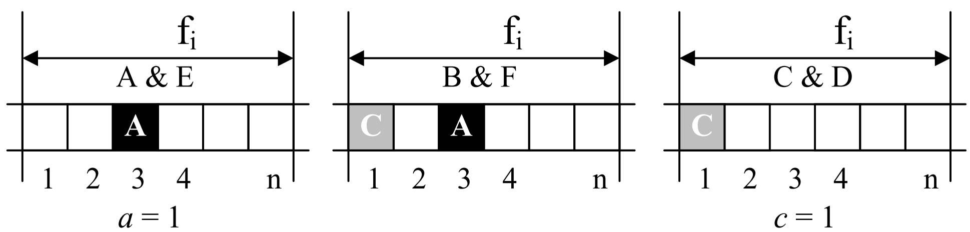
5.2.1 Analysis of the Behavior of the Reservation Based Protocols (i.e. ERA, SFRA and ESFRA) and IEEE 802.11 with respect to the Neighborhood Capture Problem

A simple MANET scenario as shown in Figure 5-7(a) is used to illustrate the NC problem. Let us consider that all stations in Figure 5-7(a) are using the IEEE 802.11 MAC protocol. Station B is one hop neighbor of both Stations A and C. Stations A and C are out of the interference ranges of each other this is why they cannot hear each other, and use the channel independently. If B wants to transmit packets, it must have to wait until both Stations A and C release the channel simultaneously. Consequently, Station B may not get access to the channel for long time, which is the NC problem. The NC problem will be severe if A and C both have many packets in their queues. Now, let see what happens if ERA or SFRA or ESFRA is applied in this scenario as a MAC protocol. According to these protocols, Station B knows about A's and C's reservation of slots as shown in Figure 5-7(c). So, B may continue its communication with any other stations (i.e. Station F in Figure 5-7(a)) by reserving a slot free from both A and C. So, Station B is out of the effect of the NC problem. For example, A is communicating with E reserving one slot in frame f_i as shown in Figure 5-7(b), and C is communicating with D reserving one slot in the same frame as shown in Figure 5-7(d). B observes both A's and C's reservations, and selects any slot from the rest of $(n-2)$ slots of the frame f_i as shown in Figure 5-7(c). But, high traffic load reduces B's chance to access to the channel. Let us consider that Station B wants to reserve 1 slot per frame, and there are n number of slots per frame, and the number of slots reserved by Station A is a, and number of slots reserved by Station C is c. If summation of all slots reserved by A and C is less than the total number of slots in a frame, B can always access the channel, which is the best case scenario for B. Therefore, the probability of B's chance to access the channel, P_B, based upon the condition $a + c < n$ is 1, this is

$$P_B = 1. \qquad \textbf{(5.2.1)}$$



(a) A simple MANET scenario to show the neighborhood capture problem.



(b) A's reservation. (c) B's observation. (d) C's reservation.

Figure 5-7: Neighborhood capture problem with example reservations of stations in a frame.

B has a probability to access the channel for the boundary conditions $a + c \geq n$ and $a + c \leq 2n$. Let us consider that A has the possibility to use the frame in U_1 ways, and C has the possibility to use the frame in U_2 ways. Therefore, the number of events in which station A is reserving a number of slots out of n slots in a frame in all possible ways is

$$U_1 = {}^{n}C_a. \qquad \textbf{(5.2.2)}$$

The number of events in which C is reserving c number of slots out of n slots in a frame in all possible ways is

$$U_2 = {}^{n}C_c. \qquad \textbf{(5.2.3)}$$

Since A and C choose the slots independently, the total number of events (i.e. U in (5.2.4)) in which A and C both use the frame is

$$U = U_1 \times U_2 = {}^{n}C_a \times {}^{n}C_c . \tag{5.2.4}$$

Let us consider only one case first, where A is reserving the first a number of slots of the frame, and C can reserve its c number of slots out of n slots in that frame in all possible ways. In this case, the number of slots remaining in the frame or not reserved by A is $(n-a)$. Let us find the number of events V in which C must use the rest of $(n-a)$ number of slots of the frame in its reservation. B will not get a chance to access to the channel in V number of events. Because, stations A and C are covering all the slots of the frame in these V events. As $c \geq (n-a)$, V can be found by taking a combination of $(c-(n-a))$ out of a slots. Therefore, the number of events in which B will not get chance to access to the channel is

$$V = {}^{a}C_{(c-n+a)} . \tag{5.2.5}$$

Now, the total number of events for all cases of A in which B will not get chance to access to the channel is

$$W = V \times {}^{n}C_a = {}^{a}C_{(c-n+a)} \times {}^{n}C_a . \tag{5.2.6}$$

Therefore, the probability of B's chance to access to the channel based upon the condition $n \leq a + c \leq 2n$ is given by

$$P_B = \frac{U - W}{U} . \tag{5.2.7}$$

Using Equations (5.2.5), (5.2.6), and (5.2.7), P_B is given by

$$P_B = \frac{n! \times (c+a-n)! - a! \times c!}{n! \times (c+a-n)!} . \tag{5.2.8}$$

According to the IEEE 802.11, Station B in Figure 5-7(a) is exposed to both Stations A and C, and forced to remain idle. As there is no guarantee that A and C will release the channel simultaneously, B's chance to access the channel is completely uncertain. So, IEEE 802.11 blocks stations like B for an indefinite time. ERA or SFRA or ESFRA provides a good channel accessing probability to these stations (i.e. B) as revealed in Equations (5.2.1) and (5.8.8).

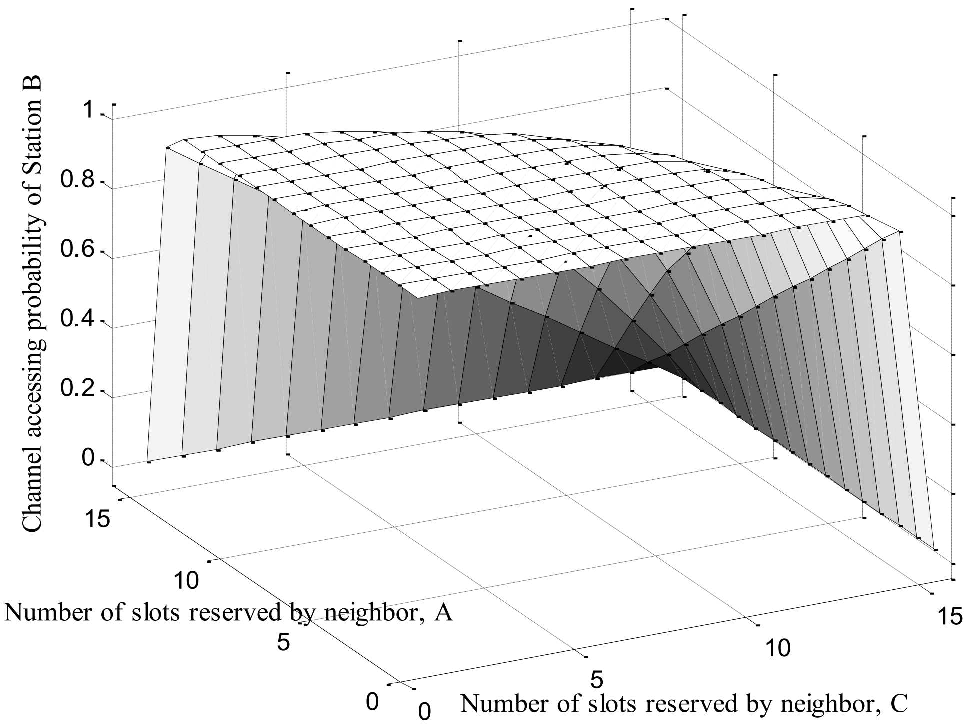


Figure 5-8: Channel accessing probability of B with the variation of the number of slots reserved by Station A and Station C.

ERA, SFRA or ESFRA has the provision to reserve more than one slot if necessary. Figure 5-8 shows a mesh diagram where Stations A and C are reserving variable numbers of slots in a 16-slot frame. The channel accessing probability of B is plotted against different combinations of slots reserved by A and C. Figure 5-8 shows that the channel accessing probability of B is always 1 for any combination of slot reservations of A and C where the summation of the number reserved slots by them is less than 16. The probability decreases if this summation is greater than 16. For example, if the number of slots reserved by A is 14, and the number of slots reserved by C is 15, the channel accessing probability of B is 0.25. The worst case occurs if either of A or C reserves the whole frame. But, that is a rare case.

Figure 5-9 shows the effect of percentage of traffic on the channel accessing probability of B. The percentage of traffic is defined as the ratio of the total number of reserved slots in a frame and total number of slots in a frame. In this case, I have considered that all stations in the contending region of B are allowed to reserve only one slot per frame. The channel accessing probability of B starts decreasing when the traffic is more than fifty percent. Figure 5-9 also shows that channel accessing probability increases for larger frame size. ERA, SFRA or ESFRA promises 100 percent channel accessing probability for the traffic less than or equal to 50 percent in the contending region. Alike the analysis in Figure 5-9, if all stations in the contending region of B are allowed to reserve only one slot per frame, the channel accessing probability of

Station B decreases with increasing the number of contending neighbours while using ERA or SFRA or ESFRA as a MAC protocol. So, unlike IEEE 802.11 MAC, ERA, SFRA and ESFRA solve the NC problem with neighbours more than two.

In Figure 5-10, every graph is drawn for a fixed percentage of loads but for different combination of slot accusation between the neighbouring stations A and C. Suppose, frame size is 16 slots. Both station A and C are operating with 50 percent load. If they use equal number of slots, they will use 8 slots each. If they use any other combination, the sum should always be 16 for 50 percent load. For the same frame size but for 70 percent load, the sum of the slot for any combination should be 24. The number of slots reserved by any one station between A and C is shown in the horizontal axis. The number of slots used by the other station can be found by subtracting from the total of the combination for each labelling in the horizontal axis.

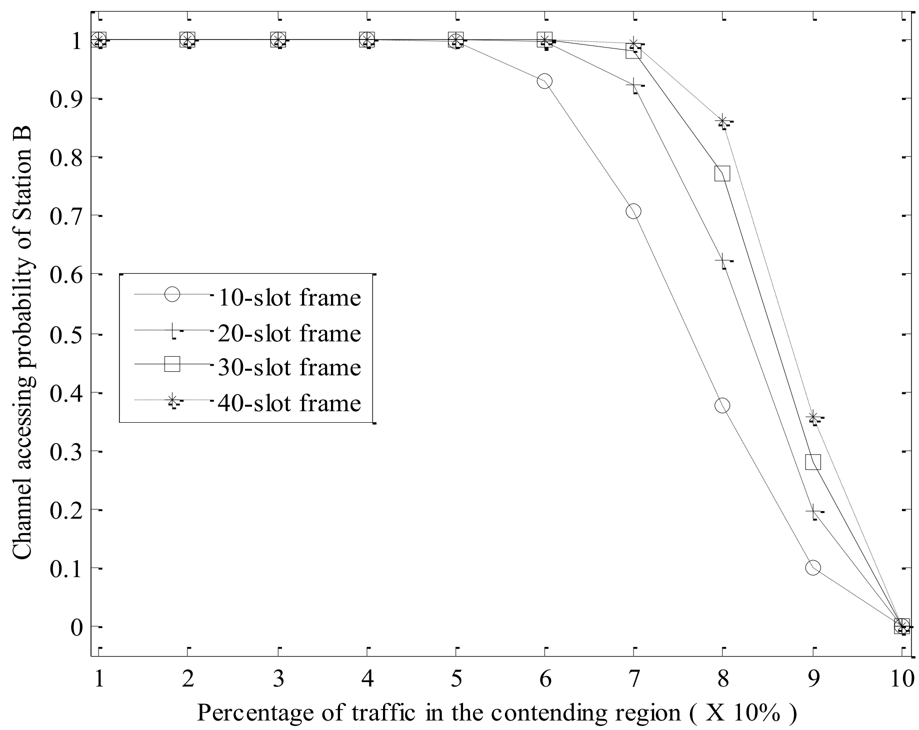


Figure 5-9: Channel accessing probability of B with the variation of traffic in the contending area.

It is evident that the 70% load curve is below the 50% load curve for both cases n=16 and n=6. One scenario is common to all curves that the probability is maximum for the combination in which station A and C reserve equal number of slots per frame, and in any other combinations the probability is decreasing. The probability is decreasing on both sides of the peak value causes the curves are drawn for any possible slot reservation combination between station A and C. In case of n=16 and 50% load probability is almost 1.0 for most of the slot reservation combinations whereas for 70% load, number of slot reservation combination decreases as well as probability is around 0.6. Almost same scenario is reflected between the curves for 50% and 70% load and n=6. If the curves with same load but different frame sizes are compared, it found that P_B is higher and more stable for larger frame size. So, larger frame size is good for combating the NC problem.

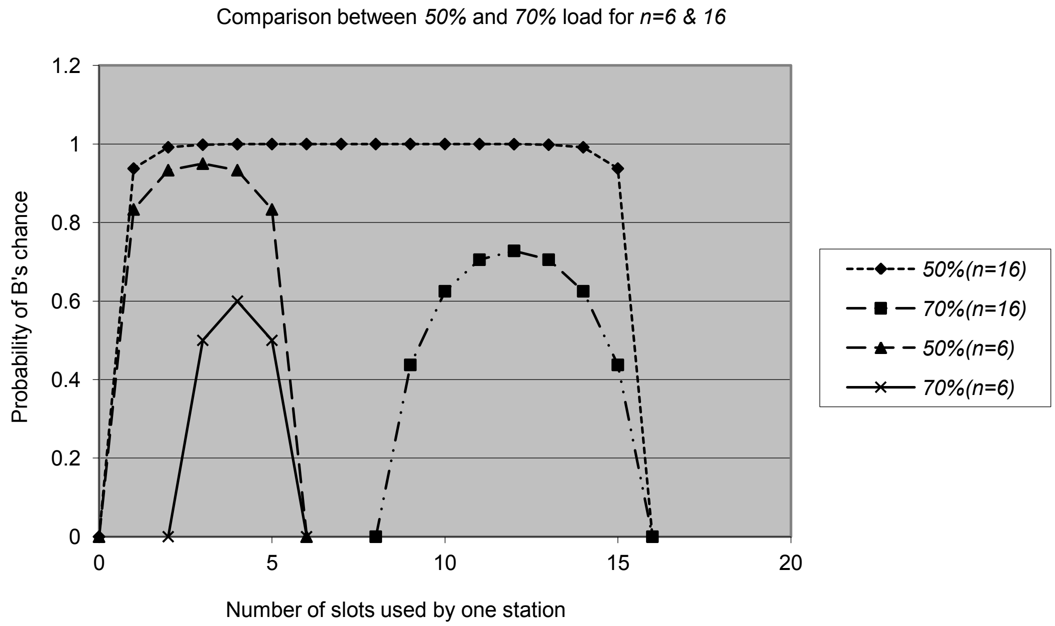


Figure 5-10: Comparison scenarios for different load and different frame size.

The discussion in this sub-section highlights that the severity of the NC problem increases with the IEEE 802.11 MAC, where as the ERA, SFRA and ESFRA MAC protocols solve the NC problem in a probabilistic manner. The stations using these MAC protocol are not severely affected by the NC problem compared to the IEEE 802.11 or similar distributed-type protocols. The next sub-section contains an analysis how ERA and SFRA reduces the collision due to the MHS problem.

5.2.2 Analysis of the Behavior of the Reservation Based Protocols (i.e. ERA and SFRA) to the Mobile Hidden Station Problem

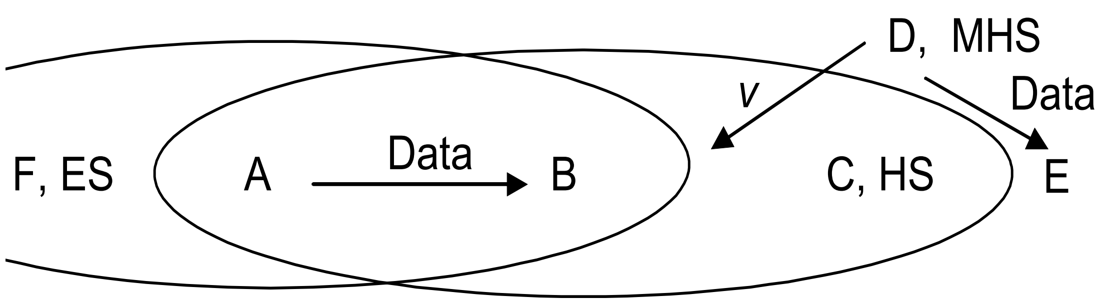


Figure 5-11: HS, ES and MHS in a MANET scenario.

The scenario in Figure 5-11 is used for the analysis in this sub-section. Let, Station A is transmitting data packet to B, and C is an HS to A. Station D is transmitting data packets to E while moving into the interference range of B as shown in Figure 5-11. So, Station D is an MHS to A. According to the principle of either ERA or SFRA, Station A reserved a slot, and is communicating with B during this slot. Similarly, Station D reserved a slot, and is communicating with Station E. If A's reservation and D's reservation are the same slot, there will be a collision with A's transmission at B. Otherwise, there is no collision with D's transmission. So, ERA and SFRA decrease the probability of collisions due to an MHS, but does not eliminate collisions. Let us consider that Station A and Station D reserve a and d number of slots per frame respectively and total number of slots per frame is n. If summation of all the slots reserved by Stations A and D is greater than the total number of slots in a frame, there is always a collision. Therefore, P_S, the probability of successful transmission by Station A based on the condition $a + d > n$ is zero. There is possibility of successful transmission by Station A for the following condition

$$a + d \leq n. \quad \textbf{(5.2.9)}$$

Let, A has a possibility to use the frame in Q_1 ways, and D has the possibility to use the frame in Q_2 ways. Therefore, number of events in which A is reserving a number of slots out of n slots in a frame in all possible ways is $Q_1 = {}^{n}C_a$. The number of events in which D is reserving d number of slots out of n slots in a frame in all possible ways is $Q_2 = {}^{n}C_d$. The total number of events (i.e. Q) in which A and D both use the frame is

$$Q = Q_1 \times Q_2 = {}^{n}C_a \times {}^{n}C_d. \quad \textbf{(5.2.10)}$$

Let us consider only one case of Station A first, where A reserves the first a number of slots of the frame, and D reserves its d number of slots out of n slots of the frame in all possible ways. In this case, number of slots remaining in the frame or not used by A is $(n - a)$. I need to find the number of events R in which Station D must reserve its d number of slots from the remaining $(n - a)$ number of slots of the frame. Station D will not cause any collision at B in this R number of events because A and D are not reserving any common slot of the frame in these R events. According to Equation (5.2.9), d is less or equal to $(n - a)$. R can be found by taking a combination of d out of $(n - a)$ slots. Therefore, the number of events in which there is no collision from MHS, D is $R = {}^{(n-a)}C_d$. So, total number of events for all cases of Station A in which there is no collision from MHS, D is

$$S = R \times {}^{n}C_a = {}^{(n-a)}C_d \times {}^{n}C_a. \quad \textbf{(5.2.11)}$$

Therefore, P_S, the probability of successful transmission by Station B based on the condition $a + d \leq n$ is given by

$$P_s = \frac{S}{Q}. \quad \textbf{(5.2.12)}$$

Using Equations (5.2.10),(5.2.11), and (5.2.12) I get

$$P_s = \frac{(n-a)! \times (n-d)!}{(n-a-d)! \times n!} . \qquad \textbf{(5.2.13)}$$

According to the principle of IEEE 802.11 MAC, Station D does not know about A's transmission to B. Whenever D will enter the interference range of B, D's transmission will collide with A's transmission. So, according to IEEE 802.11, the severity of the probability of collision due to MHSs is high whereas ERA or SFRA reduces probability of collision due to MHSs as revealed in Equation (5.2.13). Figure 5-12 shows that Station A reserves a variable number of slots in a frame, and a variable number of MHSs are affecting A's communication. It is considered that each MHS reserves one slot per frame. The increment of the number of slots reserved by A decreases the probability of its successful transmission. If A reserves only one slot for its transmission to B, A has 83 percent probability of successful transmission with 2 interfering MHSs. This probability decreases if the number of MHS increases. Figure 5-13 shows the effect of traffic intensity in the contending region of A on the probability of successful transmissions of A. Traffic intensity or percentage of traffic is defined as the ratio of total number reserved slots and total number of slots in a frame. Different curves are plotted for different number of MHSs. In this case, I have considered that all stations in the contending region of A are allowed to reserve only one slot per frame for their transmissions. One frame consists of 10 slots in this plot. The MHSs are also allowed to reserve only one slot per frame. If there is no MHS, the probability of successful transmissions using ERA or SFRA is always 100 percent as shown in the dotted line with the asterisk in Figure 5-13. For 1 MHS, it decreases linearly with the increment of the percentage of traffic. For any other cases, it decreases exponentially. Thus the analysis in this sub-section shows that ERA and SFRA work better than IEEE 802.11.

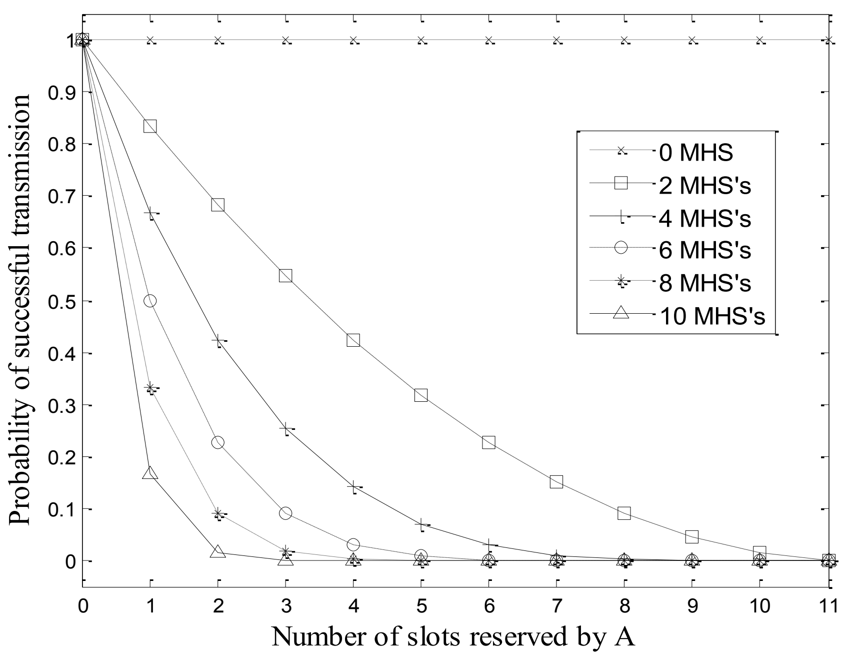


Figure 5-12: Probability of successful transmission by Station A with the variation of number of slots reserved by A.

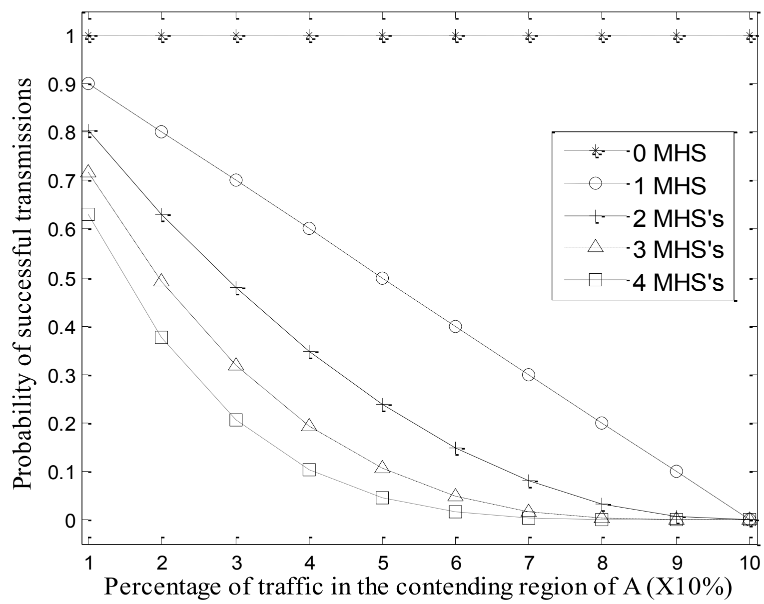


Figure 5-13: Probability of successful transmission with the variation of traffic in the contending area of A.

The probability of collision using SFRA or ERA, P_c, is given by

$$P_c = 1 - \frac{(n-a)! \times (n-d)!}{(n-a-d)! \times n!}. \quad \textbf{(5.2.14)}$$

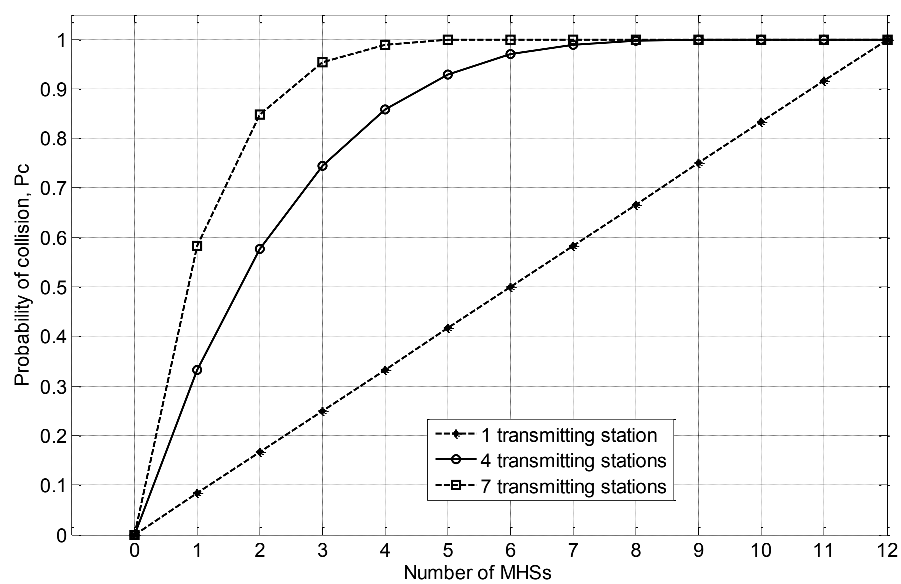


Figure 5-14: Severity of MHS problem in SFRA and ERA.

P_c is plotted versus the number of MHSs in Figure 5-14, which shows that probability of collisions due to MHSs is increasing with the number of MHSs as well as with number of transmitting stations.

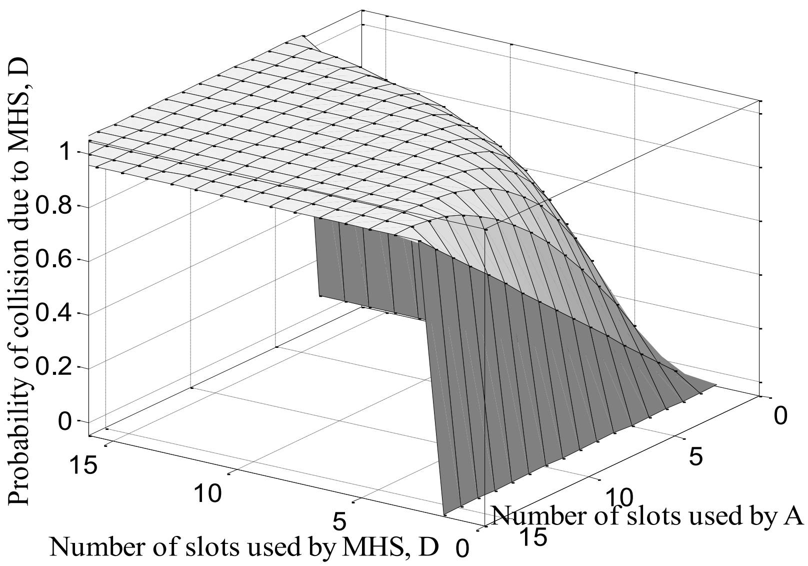


Figure 5-15: Probability of collision due to MHS, D with the variation of the number of slots reserved by A and D.

The mesh diagram in Figure 5-15 illustrates that Stations A and D are reserving variable numbers of slots in a 16-slot frame. The probability of collision at B due to MHS, D is plotted against different combinations of slots reserved by A and D. Figure 5-15 shows that the probability of collision at B is always less than one for any combination of slot reservations of A and D, where summation of the number of their reserved slots is less than or equal to 16. For example, if the number of slots reserved by A is one, and the number of slots reserved by MHS, D is one, the probability of collision at B is 0.07. So, A has 95 percent probability to make a successful transmission in this situation. The probability of collision increases if the summation of reservations by A and D increases. The worst case arises if the summation of reservations of slots by A and D exceeds the number slots in a frame (i.e. 16 in this case). In these cases, the probability of collision is 100 percent (See top flat portion of Figure 5-15). But, these are not usual cases.

So, ERA or SFRA reduces collisions due to MHSs but cannot completely solve the MHS problem.

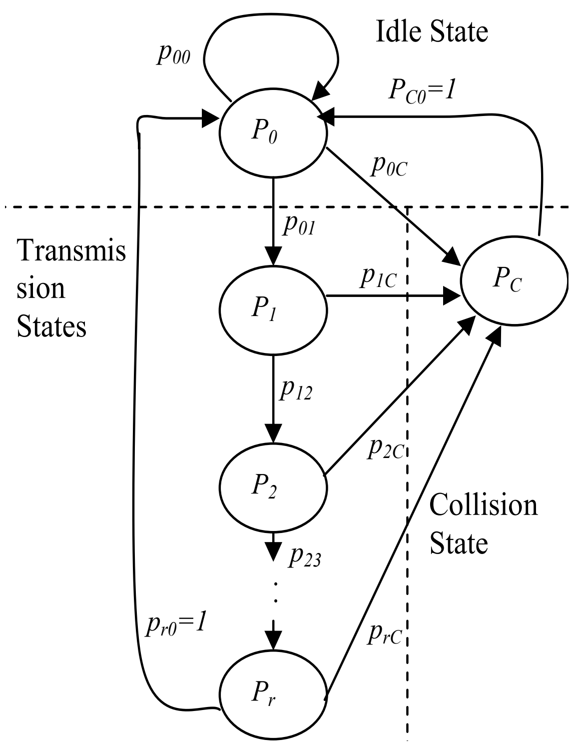
5.2.3 Markov Analysis of IEEE 802.11, SFRA and ESFRA Considering the Effect of Mobile Hidden Station

A comparative Markov analysis for SFRA, ESFRA, and IEEE 802.11 that consider the effect of the MHS problem is provided here. First, I will provide a Markov model for SFRA, then I will apply the model to ESFRA. Finally I will provide a Markov model for IEEE 802.11 MAC with considering the MHS problem. With these models, the probability of collisions, throughput and delay performances of the MAC protocols will be obtained.

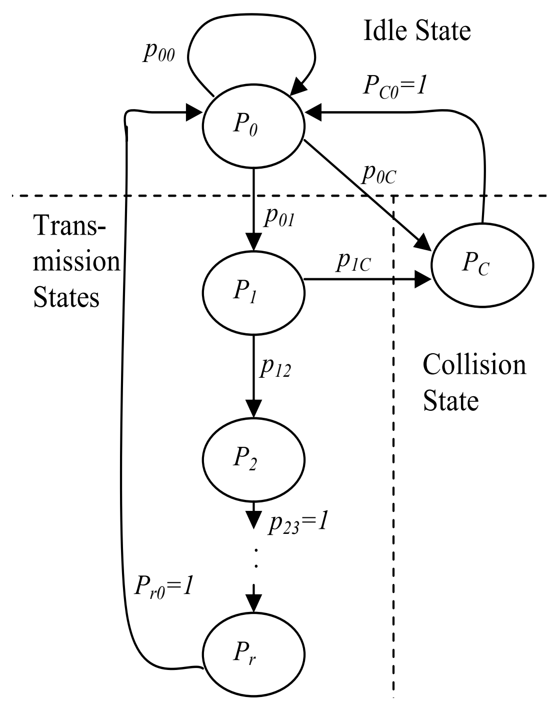
5.2.3.1 Discrete Time Markov Chain Model for SFRA

Channel (i.e., slot) accessing mechanism in SFRA is similar to slotted Aloha, and SFRA provides reservation of slots using FI, which eliminate HS problem. Each slot can be in either one of the following three states: idle, collided, and transmitting. States of the Markov chain represent the states of a slot. I am considering that N is an average number of equal priority stations contending for one slot, and all of these stations are in one contention region. The duration of one Markov chain time step is considered equal to one slot duration. As I am dealing with mobile ad hoc networks, link failures randomly occur in short intervals. Propagation delays are very small, and they are ignored. Let us consider r Markov time steps are required to transmit data from one station. The probability that an idle station attempts to send a message during a Markov time step (i.e., slot duration) is a. The probability that k stations attempt a transmission during a given slot is given by

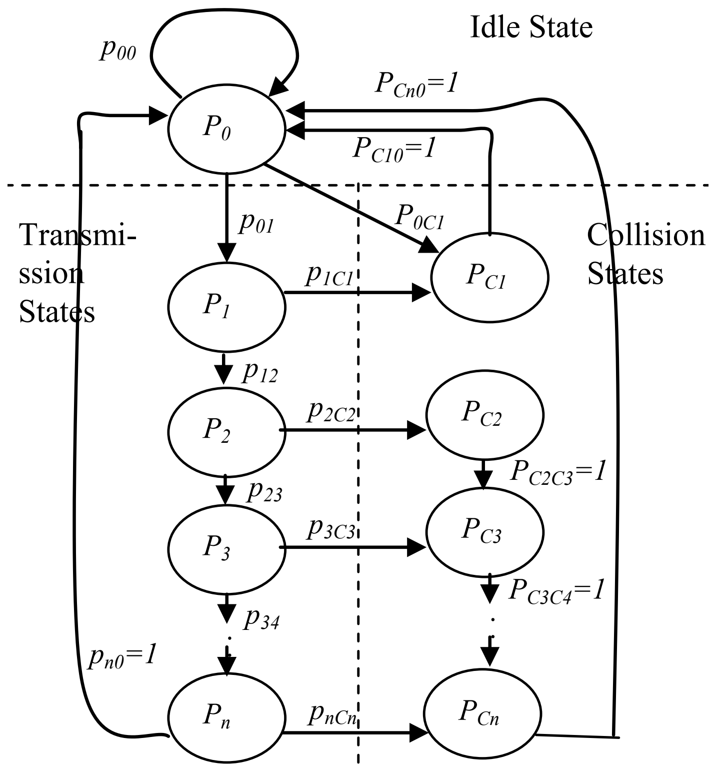
$$q_k = C_k^N a^k (1-a)^{N-k} \ . \quad \textbf{(5.2.15)}$$



(a) Markov state diagram for SFRA.



(b) Markov state diagram for ESFRA.



(c) Markov state diagram for IEEE 802.11 considering the adverse effect of MHS.

Figure 5-16: Markov state diagrams: SFRA, ESFRA and IEEE 802.11.

Figure 5-16(a) shows the state transition diagram of SFRA. There are r numbers of transmitting states (i.e., P_1 to P_r) for one reservation process. If there is no collision in any of the transmitting states in the whole reservation time, the slot will be released to idle state. As stations are mobile, there is a possibility of collision from mobile hidden stations in any of the transmitting states from P_1 to P_r . Probability of collision in each state is calculated by Equation (5.2.14), and plotted in Figure 5-14. Whenever there is a collision due to a MHS in any transmitting state, the status of a slot changes to the collided state, P_C . According to SFRA, the information transmitted in the collided slot will be lost, and the status of the slot changes to idle state because the users of this slot will transmit again simultaneously, and further collisions will be inevitable. That is why any collided slot becomes an open slot for contention in the following frame. The state diagram reflects this transition.

The channel stays in the idle state with the transition probability p_{00} as shown in the state diagram, which indicates no station has a frame to send. p_{00} is calculated from Equation (5.2.15) and given by

$$p_{00} = q_0 = (1-a)^N \ . \qquad \textbf{(5.2.16)}$$

The status of a slot changes from the idle state, P_0, to the first transmitting state, P_1, with the transition probability of p_{01} which is the probability that only one station gets access to any slot for reservation and transmission. The transition probability p_{01} is calculated using Equation (5.2.15) and given by

$$p_{01} = Na(1-a)^{N-1} \ . \qquad \textbf{(5.2.17)}$$

The status of a slot moves from the idle state, P_0, to the collided state, P_C, with the transition probability p_{0C}, which is the probability that more than one station try to access to a slot. Using Equations (5.2.16) and (5.2.17), the transition probability p_{0C} for this event is given by

$$p_{0C} = 1 - p_{00} - p_{01}. \qquad \textbf{(5.2.18)}$$

Any slot may be affected by an MHS in any of the transmission states. Whenever, the transmission in a slot is interrupted by an MHS, the status of the slot changes to the collided state, P_C, as shown in Figure 5-16(a). The transition probabilities p_{1C}, p_{2C}, … , p_{rC} in Figure 5-16(a) are representing the collision probabilities due to MHSs. The value of these probabilities can be obtained from Figure 5-14. If there is no collision in the transmitting state, P_1, the status of the slot changes to the second transmitting state, P_2, with the transition probability p_{12} thus this proceeds up to the r^{th} transmitting state, P_r. The status of a slot moves back to idle state, P_0, with the transition probability one at the end of a reservation process. I create a state transition matrix, **P,** with all the transition probabilities given by the state diagram in Figure 5-16(a). I organize the distribution vector at equilibrium as follows,

$$\pi = \begin{bmatrix} P_0 & P_1 & P_2 & . & . & . & P_{r-1} & P_r & P_C \end{bmatrix}^T . \qquad \textbf{(5.2.19)}$$

At equilibrium, the distribution vector is obtained by solving following two equations,

$$\mathrm{P}\ \pi = \pi \, , \qquad \textbf{(5.2.20)}$$

and

$$\sum \pi = 1 \ . \qquad \textbf{(5.2.21)}$$

The solution of Equations (5.2.20) and (5.2.21) are yielded

$$P_0 = \frac{1}{B}, \tag{5.2.22}$$

$$P_1 = P_2 = .. = P_r = \frac{\left(\prod_{i=1}^{r} p_{(i-1)i}\right)}{B}, \tag{5.2.23}$$

and

$$P_C = \frac{\left(p_{0C} + \sum_{i=1}^{n} p_{iC}\left(\prod_{j=1}^{i} p_{(j-1)j}\right)\right)}{B}, \tag{5.2.24}$$

where,

$$B = 2 + \sum_{i=1}^{r}\prod_{j=1}^{i} p_{(j-1)j} - p_{00} - p_{r0}\prod_{i=0}^{r} p_{(i-1)i}. \tag{5.2.25}$$

In this sub-section, a Markov model of SFRA is designed, and the state probabilities are calculated. The Markov model of ESFRA is presented in the next sub-section.

5.2.3.2 Discrete Time Markov Chain Model for ESFRA

According to the principles of ESFRA, each station uses a small back-off counter to reduce the access collisions while reserving a slot in a frame at the start of a data communication. In this model, I assume that the back-off counter (or back-off window) is composed of some small back-off slots (b-slot). There are maximum w b-slots in a back-off counter. This approach is barrowed from [63]. Whenever a station needs to reserve a slot for a packet transmission in any frame, it randomly chooses a b-slot out of w b-slots of the back-off counter. The value of w is equal to the maximum value that may be stored in the back-off counter of any station. The station with a smallest b-slot counter accesses to the channel, and sends its RTS. If CTS is successfully received, then the station starts its data transmission for this slot. All stations with other b-slots in their back-off counters sense the channel busy, decreases their back-off counter by one, and refrain from transmitting. A collision may happen if two or more stations with same back-off counters start to transmit simultaneously. However, the likelihood of this event is small since the number of stations with same back-off counter is low. If the station with b-slot 0 in its back-off counter remains idle, the station with b-slot 1 in its back-off counter can transmit based upon the requirement of the reservation. The same procedure is repeated for the stations with higher counter values waiting for accessing the channel for reservations. A slot is considered idle if it remains unused, transmitting if it is reserved or collided if there is any collision. ESFRA eliminates collisions due to HSs and MHSs with its SF mechanism. A missing CTS packet is considered as a collision in ESFRA for this analysis. Since the future state of a slot depends on its present history, the state of this slot can be modeled using Markov chain analysis. The state of the Markov chain represents the state of a slot whether that is idle, transmitting or collided. For this modeling, it is assumed that there are N stations, and they have equal probabilities to access to the channel. The duration of one b-slot in the back-off window is considered equal to the time required for one RTS/CTS handshaking, and this duration is one Markov chain time step. As I am dealing with ad hoc networks, the single hop propagation delay can be considered very small. The lengths of RTS and CTS packets are much smaller compared to a slot transmission time, and are only needed to access and reserve an idle (i.e., free) slot. Let us consider that r Markov time steps are required to cover one reservation process. The probability that an idle station accesses to an idle slot during one Markov time step is a. As, the maximum value that can be stored in a back-off counter is w, and if total number of contending stations, N, is greater than w, the number of stations who may select the same slot is given by

$$N' = \frac{N}{w} \ . \tag{5.2.26}$$

Thus, the number of stations that compete to access a slot is reduced from N to N'. The probability that k stations attempt a transmission in an idle slot is given by

$$q_k = C_k^{N'} a^k (1-a)^{N'-k} \ . \tag{5.2.27}$$

Figure 5-16(b) shows the state transition diagram of Markov chain for ESFRA in MANET. If no station needs to reserve a slot, the status of a slot remains idle. If a station successfully acquires a slot using its back-off counter mechanism, it reserves its slot for r Markov chain time steps to transmit its message, and the status of a slot changes to transmitting state. The transition probability to move from the idle state to the 1st transmitting state is p_{01}. The status of a slot changes to the collision state in two ways. First, if more than one station select the same b-slot (i.e., same b-slot out of w b-slots according to my model), the status of a slot changes from the idle state to the collided state with the transition probability p_{0C} as shown in Figure 5-16(b). Second, if the CTS is not received by the sender. This may happen in two ways: (i) if there is a RTS collision at the expected receiver or (ii) if the expected receiver is busy. Both cases are considered as a collision in this model, and either of these two cases causes the status of a slot to change from the 1st transmitting state to the collided state with the transition probability p_{1C} as shown in Figure 5-16(b). Whenever the status of a slot is in the collided state, it must move to the idle state with the transition probability 1. If there is no collision in the 1st transmitting state, the status of a slot traverses all the remaining transmitting states with the transition probabilities p_{12}, p_{23}, … , $p_{(r-1)r}$ as shown in Figure 5-16(b). The status of a slot must move to the idle state at the end of the r^{th} transmitting state. The status of a slot stays in the idle state with the transition probability p_{00}, which is the probability that no station has a message to send. Using Equations (5.2.26) and (5.2.27), the transition probability p_{00} for this model is given by

$$p_{00} = {q_0}^w = (1-a)^N \ . \tag{5.2.28}$$

The calculation of the transition probability p_{01} is based on the selection of a b-slot in the back-off counter. This is the probability in which a station selects a b-slot in its back-off counter, and requests a transmission, and all other stations select the previous b-slots in their back-off counters, and do not request to access to the slot. The transition probability p_{01} for this event as calculated in [63] is given by

$$p_{01} = \frac{q_1(1-q_0{}^{w})}{1-q_0}. \quad \textbf{(5.2.29)}$$

Using Equations (5.2.28) and (5.2.29), the transition probability p_{0C} for this model is given by

$$p_{0C} = 1 - p_{00} - p_{01}. \quad \textbf{(5.2.30)}$$

I create a state transition matrix, **P** for the transition probabilities given in the state diagram. The distribution vector of the states of the channel at equilibrium is organized as

$$\pi = \begin{bmatrix} P_0 & P_1 & P_2 & . & . & . & P_{r-1} & P_r & P_C \end{bmatrix}^T \quad \textbf{(5.2.31)}$$

At equilibrium, the distribution vector is obtained by solving the following two equations

$$\mathrm{P}\ \pi = \pi\ , \quad \textbf{(5.2.32)}$$

and

$$\sum \pi = 1\ . \quad \textbf{(5.2.33)}$$

After solving Equations (5.2.32) and (5.2.33) I get

$$P_0 = \frac{1}{A}\ , \quad \textbf{(5.2.34)}$$

$$P_1 = \frac{p_{01}}{A} \ , \quad \textbf{(5.2.35)}$$

$$P_2 = \ldots = P_r = \frac{p_{01}p_{12}}{A} \ , \quad \textbf{(5.2.36)}$$

and

$$P_C = \frac{1 - p_{00} - p_{01} + p_{01}p_{1C}}{A} \ , \quad \textbf{(5.2.37)}$$

where,

$$A = 2 + p_{01} + (r-2)p_{01}p_{12} - p_{00}. \quad \textbf{(5.2.38)}$$

In this sub-section, a Markov model of ESFRA was presented, and the state probabilities were calculated. Markov model of IEEE 802.11 MAC will be presented in the next sub-section.

5.2.3.3 Discrete Time Markov Chain Model for IEEE 802.11 MAC with MHS.

IEEE 802.11 is one of the widely used MAC protocols for wireless access, and it is considered for mobile systems under the new standardization process of IEEE 802.11p. That is why it is important to investigate how IEEE 802.11 MAC will behave with the MHS problem. This will provide a benchmark for ESFRA as well. The author in [63] presented a Markov model of only IEEE 802.11: DCF without considering RTS/CTS handshaking. This modeling and techniques were used in modeling of SFRA and ESFRA in the previous sections too. However, the model presented in [63] for IEEE 802.11 MAC does not capture the effect of HS and MHS problems. Here, the model will be enhanced; and HS and MHS problems will be introduced.

Let us assume that there are N equal priority stations that contend for a channel access. The duration of one Markov time step is considered equal to the time it takes a station to sense the presence of a carrier plus the amount of time required for RTS/CTS handshaking, and one frame transmission takes several Markov chain time steps. Let, n Markov chain time steps are required to transmit one frame.

IEEE 802.11 channel may be in one of three states: idle, collided, or transmitting. If no station has a frame to send, the channel remains idle. The status of a channel changes to any of the other two states if the stations have frames to transmit. If a station successfully acquires the channel using its back-off counter mechanism, it exchanges its RTS/CTS in the first transmitting state (i.e., P_1). The status of the channel changes to the first transmitting state with the transition probability p_{01}. If RTS/CTS handshaking is successful, it transmits its frame in the next $(n-1)$ Markov chain time steps, and the status of the channel traverses $(n-1)$ transmitting states with the transition probabilities p_{12} , p_{23} , …, and $p_{(n-1)n}$ as illustrated in Figure 5-16(c). The status of the channel must change to the idle state at the end of a frame transmission at the n^{th} transmitting state. If there is a collision at the time of accessing, the status of the channel changes from the idle state, P_0, to the collided state, P_{C1}, with the transition probability p_{0C1}. The channel is affected by the loss of an RTS or a CTS packet in the transmitting state, P_1. This loss changes the status of the channel from the transmitting state, P_1, to the collided state, P_{C1}. The transmitting state, P_1 is also affected by the MHSs. This also changes the status of the channel from the transmitting state, P_1, to the collided state, P_{C1}. Whenever the status of the channel is in the collision state, P_{C1}, it changes to the idle state, P_0, with the transition probability one.

Each of the rest $(n-1)$ transmitting states might be affected by only MHSs, this is why each of the rest $(n-1)$ transmitting states must have a corresponding collided state e.g. P_{C2}, P_{C3}, ... and P_{Cn}. Whenever there is a collision due to MHSs in any of the $(n-1)$ transmitting states (i.e., p_2, p_3, …. or p_n), the status of the channel must transit to the corresponding collided state (i.e., P_{C2}, P_{C3}, ... or P_{Cn}) with a transition probability (i.e., p_{2C2}, p_{3C3}, …. or p_{nCn}). According to IEEE 802.11, the rest of the frame is lost, and the status of the channel changes to idle state, P_0, after traversing the remaining collided states. A state transition matrix, **P**, can be obtained with the transition probabilities given by the state diagram in Figure 5-16(c).

The state distribution vector, π, is in the following from:

$$\pi = \left[P_0 \quad P_1 \quad P_2 \quad . \quad P_n . \quad .P_{C1} \quad P_{C2} \quad . \quad P_{Cn} \right]^T . \tag{5.2.39}$$

At the equilibrium, the distribution vector is obtained by solving the following equations:

$$\text{P } \pi = \pi , \tag{5.2.40}$$

and

$$\sum \pi = 1 . \tag{5.2.41}$$

The solution of Equations (5.2.40) and (5.2.41) gives

$$P_0 = \frac{1}{D} \ , \tag{5.2.42}$$

$$P_1 = P_2 = .. = P_n = \frac{\left(\prod_{i=1}^{n} p_{(i-1)i} \right)}{D} , \tag{5.2.43}$$

$$P_{C1} = \frac{(p_{0C1} + p_{01}p_{1C1})}{D}, \quad \textbf{(5.2.44)}$$

and

$$P_{C2} = .. = P_{Cn} = \frac{\left(\sum_{i=2}^{n} \left(\prod_{j=1}^{i} p_{(j-1)j} \right) p_{iCi} \right)}{D}, \quad \textbf{(5.2.45)}$$

where,

$$D = 1 + \sum_{i=1}^{n} \prod_{j=1}^{i} p_{(j-1)j} + p_{0C1} + p_{01}p_{1C1} + \sum_{v=2}^{n} \left(\sum_{i=2}^{v} \left(\prod_{j=1}^{i} p_{(j-1)j} \right) p_{iCi} \right). \quad \textbf{(5.2.46)}$$

With these models, the next sub-section contains the comparison among the three MAC protocols SFRA, ESFRA and IEEE 802.11 considering the effect of MHS problem.

5.2.3.4 Results of Markov Analysis on MHS Problem: Comparative Behavior of IEEE 802.11, SFRA and ESFRA

ESFRA is compared with SFRA and IEEE 802.11 in terms of throughput, total delay, and collision probability to observe the effect of the MHS problem. The throughput (i.e., T) is defined by probability of any station to be in the transmitting states for an effective data transmission. The total delay is defined as the summation of the access delay (i.e., T_a), and the transmission delay. The access delay is defined as the total amount of time required for the retransmission attempts before making a successful transmission of a frame. In order to calculate the access delay, access probability (i.e., P_a) needs to be calculated first. The access probability is defined in [63] and given by

$$P_a = \frac{T}{a.N}, \quad \textbf{(5.2.47)}$$

where N is the number of contending stations, and a is the probability that a station attempts to access to the channel. In this analysis, a = 0.1 and N = 15. For SFRA and ESFRA, it is considered that there are 8 slots in a frame. The average number of attempts (i.e., n_a) for a successful transmission is given by [63] as well and follows

$$n_a = \sum_{i=0}^{\alpha} i \times (1 - P_a)^i \times P_a = \frac{(1 - P_a)}{P_a}. \quad \textbf{(5.2.48)}$$

The access delay is obtained by the average number of attempts for a successful transmission, and duration of one Markov time step, T_M . Thus,

$$T_a = n_a \times T_M . \tag{5.2.49}$$

The collision probability is defined by the probability of any station to be in the collided states.

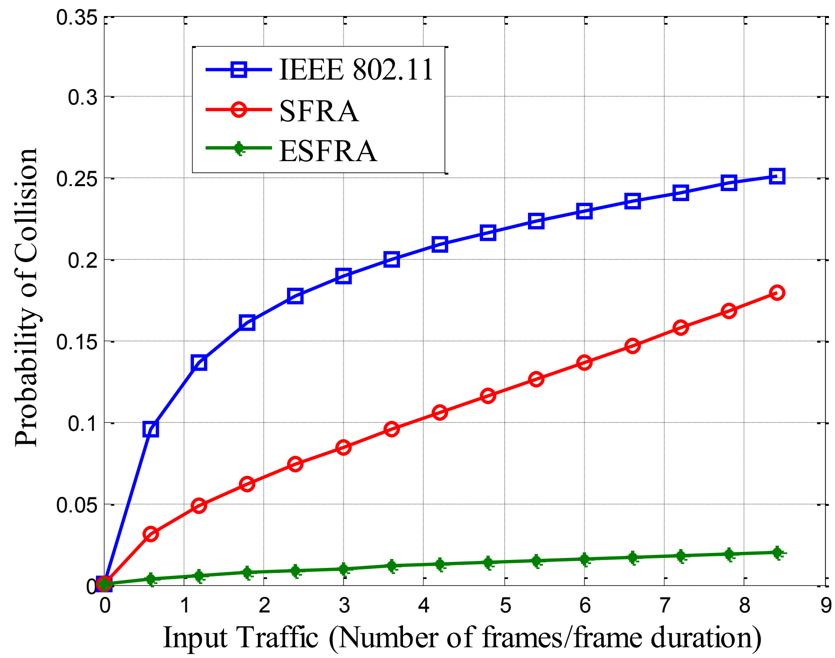


Figure 5-17: Comparison of probability of collision.

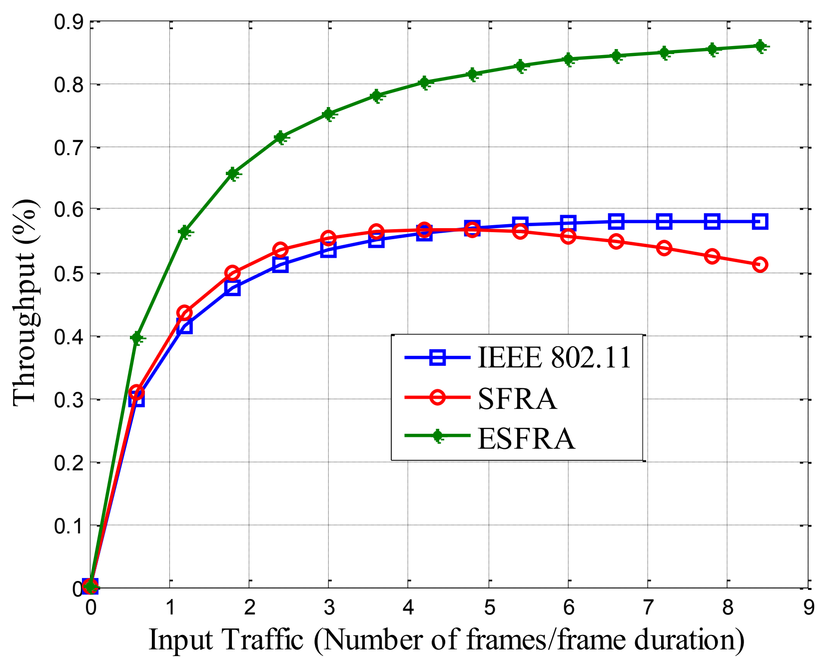


Figure 5-18: Comparison of throughputs of IEEE 802.11, SFRA and ESFRA.

With these performance metrics, Figure 5-17 provides the comparison of the collision probabilities for ESFRA, SFRA and IEEE 802.11. The probability of collision in ESFRA is two percent when the input traffic is 8 frames per frame duration. The probability of collision using SFRA is 16 percent more than ESFRA when the input traffic is 8. This probability includes both collisions due to MHSs and unsuccessful transmission attempts due to the busy recipients in SFRA. The collision probability for IEEE 802.11 with the same number of mobile stations is 25 percent, which is ten percent more than SFRA and 23 percent more than ESFRA. When there is a collision in IEEE 802.11, the whole frame is lost, but only the transmission in a collided slot is lost in ESFRA and SFRA. The difference between ESFRA and SFRA is significant too. ESFRA has a better access scheme for the idle slots, which reduces the collisions, at the same time, ESFRA does not have collisions due to MHSs.

As ESFRA is free from the collisions due to MHSs, there is a significant improvement in the throughput for ESFRA. Figure 5-18 is provided to show the normalized throughputs of the MAC protocols. The throughput of ESFRA is 87 percent, which is 28 percent more than that of IEEE 802.11 and 36 percent more than that of SFRA when the input traffic is 8. Figure 5-19 shows that the total delay is significantly decreased in ESFRA. When the input traffic is 8, the total time required to transmit a frame using ESFRA is 16 Markov time steps, which is 16.5 Markov time steps lower than SFRA, and 16 Markov time steps lower than IEEE 802.11.

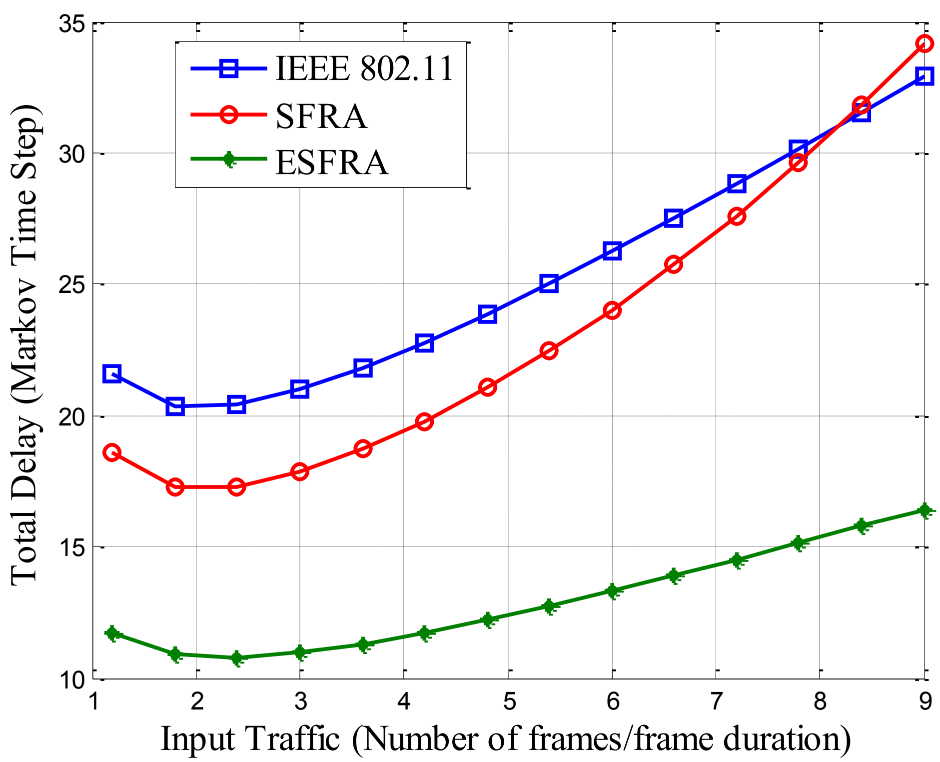


Figure 5-19: Comparison of total delay.

5.2.4 Analysis of the Behavior of the Reservation Based Protocols (i.e. ERA and SFRA) to Asymmetric Radio Link Problem

A detailed quantitative analysis in this sub-section shows how reservation based protocols (i.e. ERA and SFRA) is affected by collisions due to the ARL problem.

The scenario in Figure 2-5 is used for the analysis in this sub-section. Let, Station A is transmitting data packet to B, and C and D are HSs to A. According to the principle of ERA or SFRA, Station A reserved a slot, and is communicating with B during this slot. Similarly, Stations C and D reserve their slots in the frame. A's reservation is known to B and C according to the mechanisms of both ERA and SFRA. Station D does not know about A's reservation due to asymmetric radio links of the stations. If A's reservation and D's reservation are the same slot, there will be a collision with A's transmission at B. Otherwise, there is no collision with D's transmission. So, ERA or SFRA does not solve HS problem due to ARL. Let us consider that Stations A, B, C and D reserve a, b, c and d number of slots per frame respectively, and total number of slots per frame is n. If summation of all the slots reserved by Stations A, B, C and D is greater than the total number of slots in a frame, there is always a collision. Therefore, P_c, the probability of collision by Station A based on the condition $a + b + c + d > n$ is certain, (i.e., $P_c = 1$). There is possibility of successful transmission by Station A for the following condition

$$a+b+c+d \leq n. \qquad \textbf{(5.2.50)}$$

Let, A has a possibility to use the frame in Q_1 ways, and D has the possibility to use the frame in Q_2 ways. Both A and D know about B and C's reservation. Therefore, Let us assume $Q_1 = {}^{n-b-c}C_a$ is a number of slots out of n slots in a frame in all possible ways that A reserves is. Similarly, $Q_2 = {}^{n-b-c}C_d$ is the number of events that D is reserving d number of slots out of n slots in a frame in all possible ways. Total number of events (i.e. Q) in which both A and D use in the frame is given by

$$Q = Q_1 \times Q_2 = {}^{n-b-c}C_a \times {}^{n-b-c}C_d . \qquad \textbf{(5.2.51)}$$

First, let us consider only one case of Station A, where A reserves the first a number of slots of the frame, B uses any number of slots from the rest of the slots, C uses any c number of slots from the rest of the slots, and D reserves its d number of slots from rest of n slots of the frame in all possible ways. In this case, the number of slots remaining in the frame or not used by A, B and C is $(n - a - b - c)$. I need to find the number of events R in which Station D must reserve its d number of slots from the remaining $(n - a - b - c)$ number of slots of the frame. Station D will not cause any collision at B in this R number of events because A and D are not reserving any common slot of the frame in these R events. According to Equation (5.2.50), d is less or equal to $(n - a - b - c)$. R can be found by taking a combination of d out of $(n - a - b - c)$ slots. Therefore, the number of events in which there is no collision from an HS, namely D, is $R = {}^{(n-a-b-c)}C_d$. So, total number of events for all cases of Station A in which there is no collision from D is

$$S = R \times {}^{n-b-c}C_a = {}^{(n-a-b-c)}C_d \times {}^{n-b-c}C_a . \qquad \textbf{(5.2.52)}$$

Therefore, P_s, the probability of successful transmission by Station A based on the condition $a + b + c + d \leq n$ is given by

$$P_s = \frac{S}{Q}. \tag{5.2.53}$$

Using Equations (5.2.51), (5.2.52), and (5.2.53) I get P_s as

$$P_s = \frac{(n-a-b-c)! \times (n-b-c-d)!}{(n-a-b-c-d)! \times (n-b-c)!}. \tag{5.2.54}$$

Figure 5-20 shows the probability of collision if transmitting stations like A increases and/or HSs like D increases in the scenario in Figure 2-5. For the analysis in Figure 5-20, I consider that there is only one station like Station B and one station like Station C. Let us consider that all stations in the collision domain reserves one slot per frame. Figure 5-20 shows that probability of collision increases with increasing with number of transmitting stations like A as well as HSs due to ARL like D. On the other hand, ESFRA confirms the propagation of the slot reservation information up to three hops away that removes the collisions HSs due to the ARLs, and the probability of collision due to HSs due to ARLs is zero.

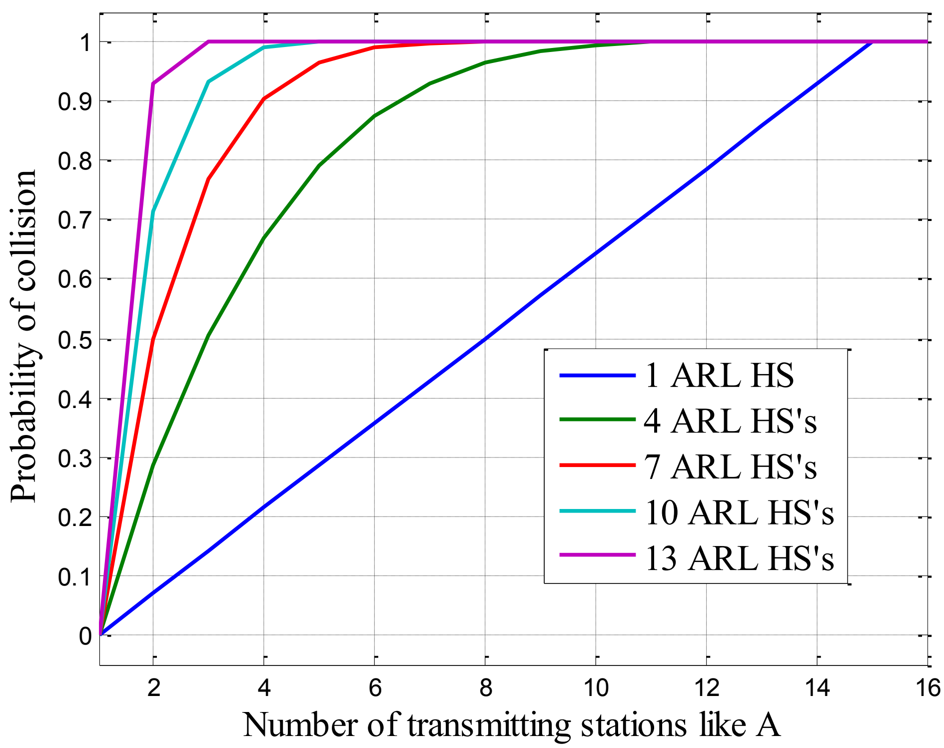


Figure 5-20: Probability of collision if SFRA is used as a MAC protocol in an asymmetric radio link scenario.

Figure 5-21 illustrates how packet transmissions are affected by the total number of stations in the collision domain if ERA or SFRA is used as a MAC protocol. It is considered that all the stations like A, B, C and D in Figure 2-5 are increasing in numbers. As the stations like D are not addressed by ERA or

SFRA, their transmissions are responsible for the collisions at the receivers like B. If total number of stations in the collision domain increases, the probability of collision increases significantly as shown in Figure 5-21. Figure 5-21 also shows that high message rate increases the probability of collision due to the ARL problem.

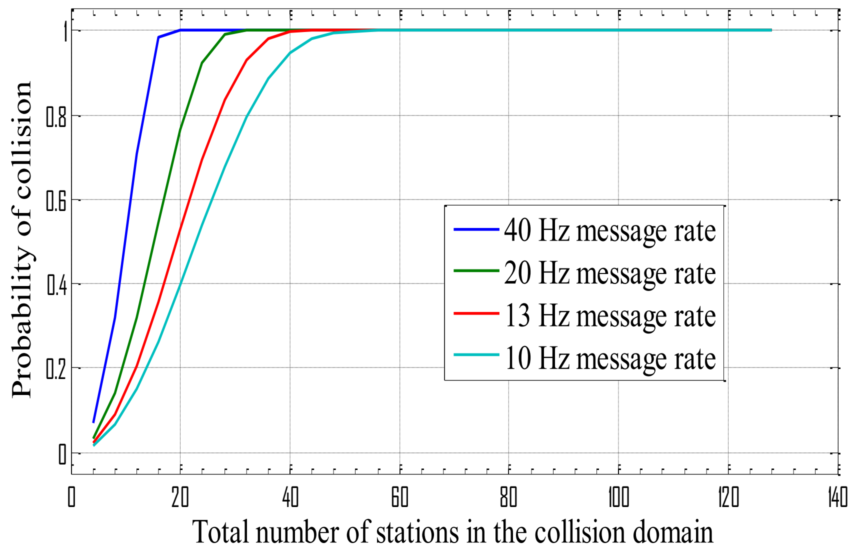


Figure 5-21: Probability of collision with the variation of the total number of mobile stations in the contending area of A.

5.3 Cross-layer

ESFRA is modified to CESFRA to make it efficient for safety critical information dissemination in vehicular communication. The cross-layer behavior of CESFRA comprises the behaviors of the network layer and the MAC layer, and the mechanism of the MAC part of CESFRA is same as ESFRA. There are basically two types of communication in DSRC/WAVE systems e.g. safety critical information dissemination by broadcasting and vehicle to RSU data communication. The DSRC/WAVE systems use IEEE 802.11p broadcast for safety critical information dissemination and IEEE 802.11p MAC for vehicle to RSU data communication. So, the analysis in this sub-section is divided into two parts, e.g. (1) Sub-section 5.3.1 contains the comparison between IEEE 802.11 MAC and CESFRA MAC; (2) Sub-section 5.3.2 contains the comparison between IEEE 802.11p broadcast and CESFRA MAC. Because the service differentiation (i.e. quality of service) part of IEEE 802.11p is omitted in this simulation, the term IEEE 802.11 MAC is used instead of IEEE 802.11p MAC in Sub-section 5.3.1. In all analyses, the physical layer is IEEE 802.11p.

5.3.1 Simulation: Comparative Behavior of IEEE 802.11 MAC and CESFRA MAC to Mobile Hidden Station and Asymmetric Radio Link Problems

A comparative view of CESFRA MAC and IEEE 802.11 MAC is presented in this section to reveal their performances in communication between vehicles and RSUs. Both protocols are simulated in OMNeT++ with MiXiM modeling framework [64]. The IEEE 802.11p physical layer available in MiXiM is used as the physical layer in both protocols. Two separate simulations are done in two different scenario to reveal the adverse effects of the MHS problem and the ARL problem separately. One scenario reflects the MHS problem while the other one reflects the ARL problem. Ten high speed (30 meter/second) mobile stations are moved from opposite direction as in a highway to create the MHS problem in one simulation. The other simulation uses ten stations with different transmission ranges (i.e. 300 meter and 150 meter) to create the ARL problem. In both simulations, the application layer packet size used is 512 Byte, and the distribution of the incoming packets is binomial distribution. The simulations are always executed for 50 seconds. The performances of CESFRA MAC is compared with IEEE 802.11 MAC using four metrics e.g. channel utilization, throughput, average packet delay and total number of packets successfully transmitted in both simulations. Channel utilization is defined as the percentage of the utilization of the channel. Throughput is defined as the average number of bits successfully transmitted per unit duration. Average packet delay is defined by the average time required for the successful one hop transmission of a packet. All the metrics are measured with the variation of input traffic to the source stations. Input traffic is defined as the number of incoming packets per packet duration.

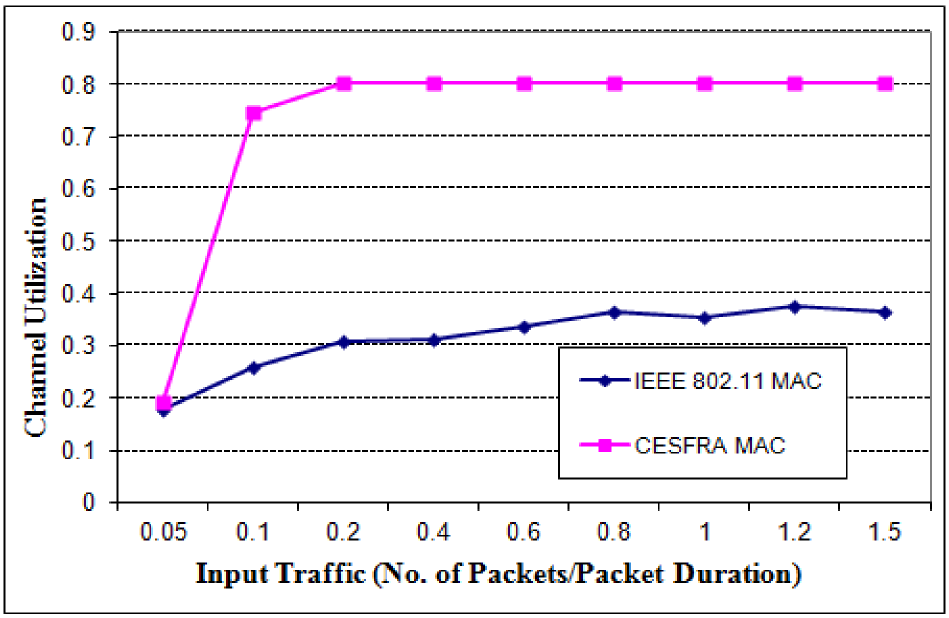


Figure 5-22: Comparison of channel utilization considering the effect of MHS problem.

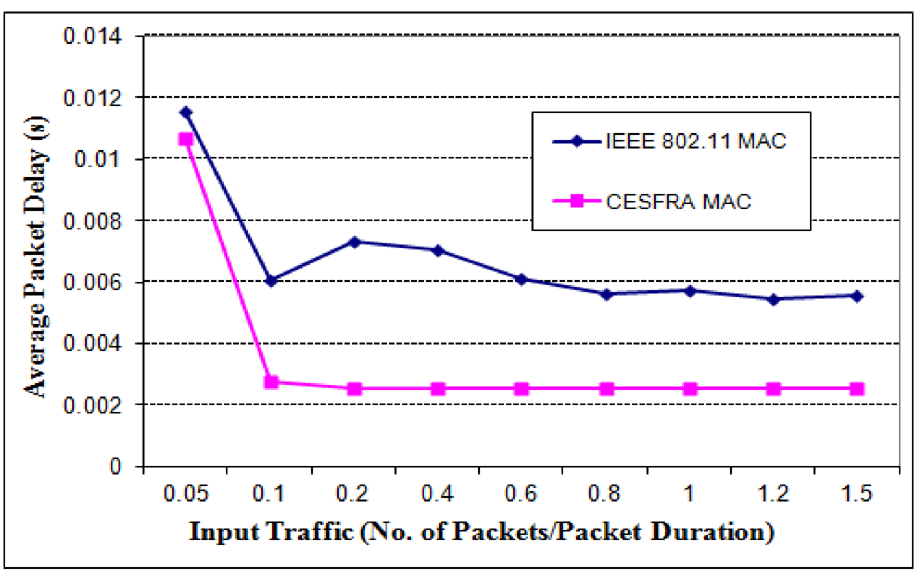


Figure 5-23: Comparison of average packet delay considering the effect of MHS problem.

Figure 5-22 illustrates that CESFRA MAC provides about seventy five percent channel utilization when input traffic is 0.1 packet per packet duration. It reaches eighty percent at input traffic 0.2. The channel utilization of IEEE 802.11 MAC increases up to thirty eight percent when input traffic is 0.8. The channel utilization of CESFRA MAC is forty two percent more than IEEE 802.11 MAC at input traffic 0.8. The consideration of the delay of a safety critical packet transmission to neighbors is important in DSRC/WAVE systems. The average packet delay for CESFRA MAC is about two millisecond whereas it is about six millisecond for IEEE 802.11 MAC as compared in Figure 5-23. CESFRA MAC improves the safety systems in delay consideration.

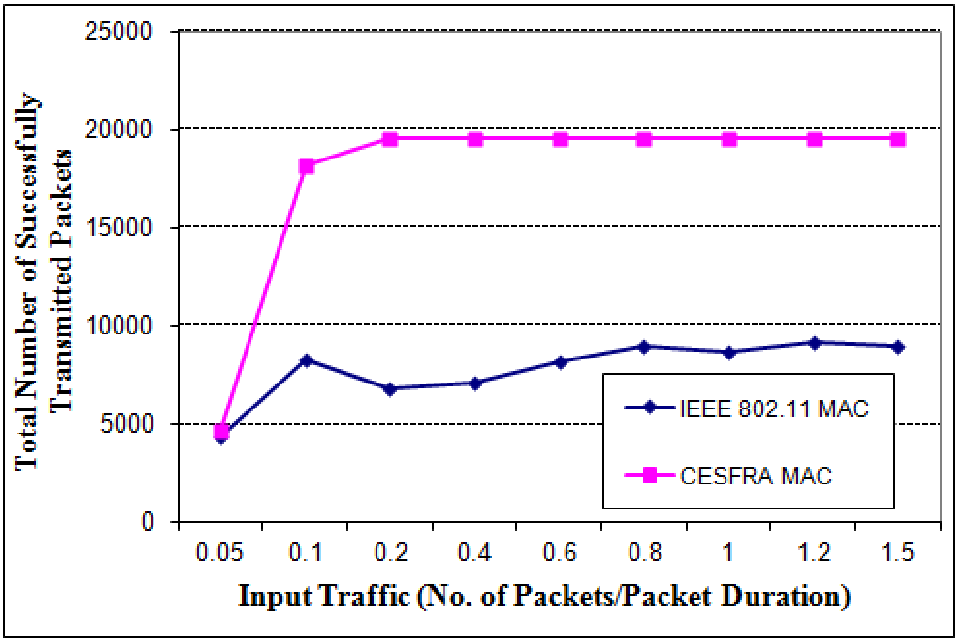


Figure 5-24: Total number of successfully transmitted packets considering the effect of MHS problem.

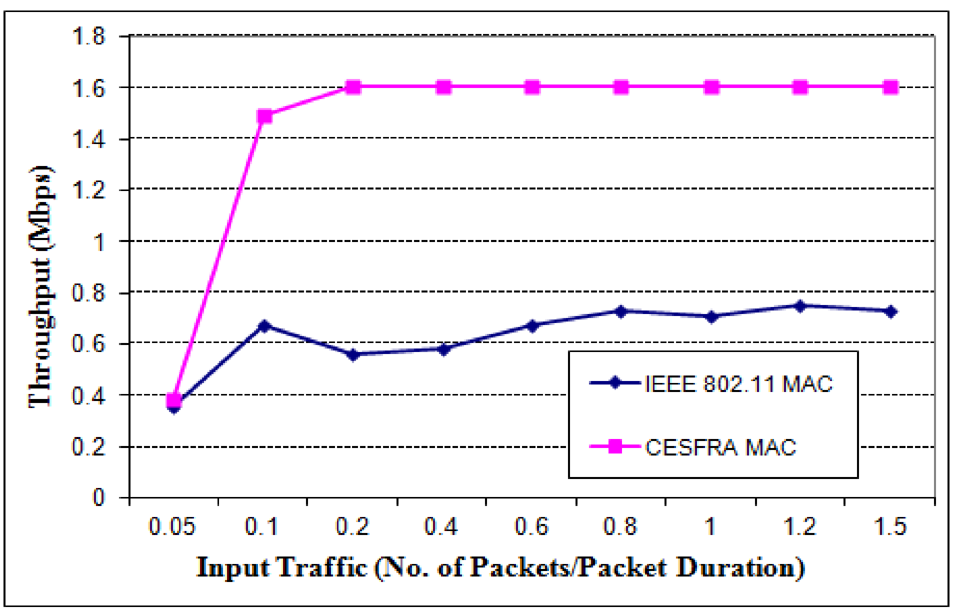


Figure 5-25: Comparison of throughput considering the effect of MHS problem.

The simulation time is fifty second for every input traffic. CESFRA MAC successfully transmits about 19000 packets in each simulation after input traffic 0.1 whereas IEEE 802.11 MAC reaches its maximum transmission of about 8000 packets per simulation at input traffic 1 (See Figure 5-24). CESFRA MAC performs more than fifty percent successful packet transmission. Figure 5-25 shows that Throughputs of both protocols are low for low traffic, and these are increasing up to saturation. For higher packet arrival rate, CESFRA MAC is providing about 0.9 Mbps more throughput than IEEE 802.11 MAC. The results in Figure 5-22, 5-21, 5-22 and 5-23 show that CESFRA MAC outperforms IEEE 802.11 MAC in solving the MHS problem. As MHSs are situated 3 hops apart from the sender, CESFRA MAC manages to send the MAC control information up to the 3rd hop to make MHSs aware of the communication, where as IEEE 802.11 MAC manages to pass MAC control information up to the 2nd hop.

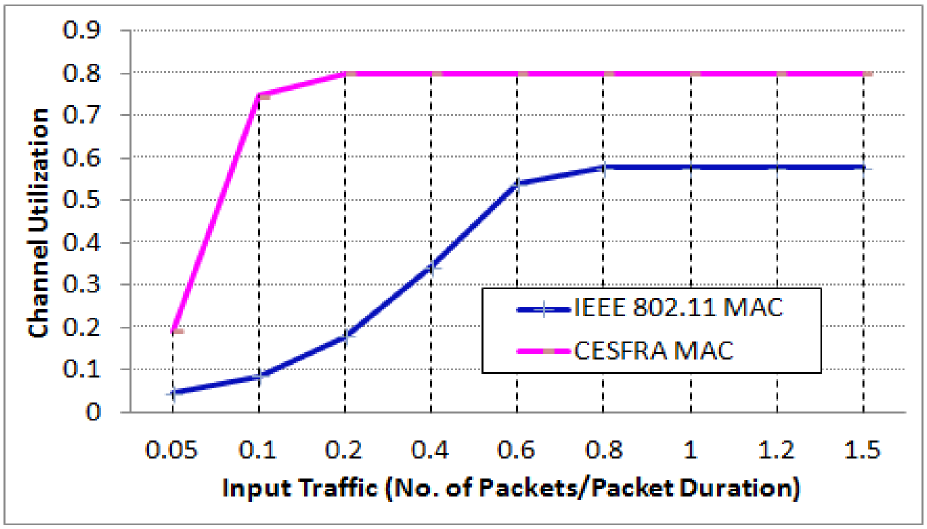


Figure 5-26: Effect of ARL problem on channel utilization.

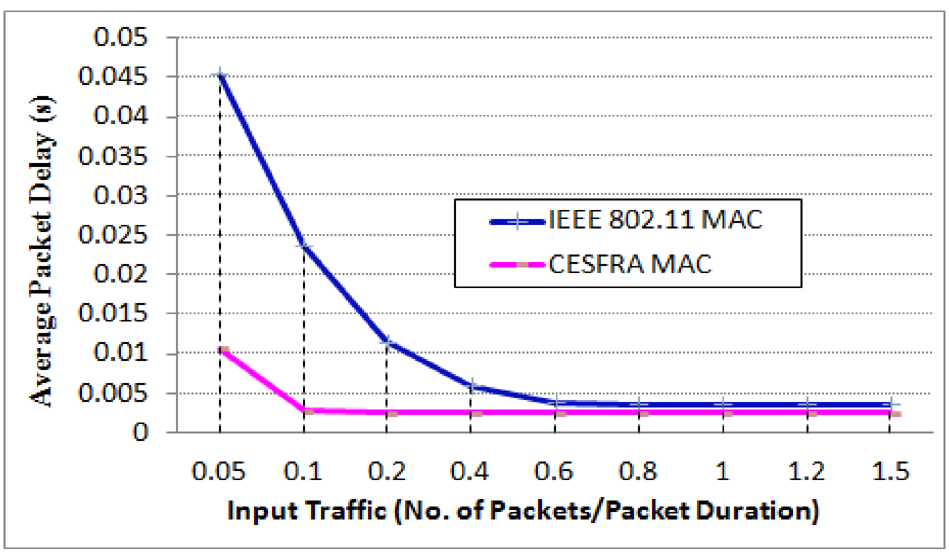


Figure 5-27: Effect of ARL problem on average packet delay.

The analysis in Figure 5-26, 5-25, 5-26, and 5-27 illustrates the adverse effect of ARL problems. As discussed in Sub-section 2.4, asymmetric radio links of different stations creates some hidden stations which are not recognized by IEEE 802.11 MAC. Those HSs make collisions on the receiver side. Figure 5-26 shows that CESFRA MAC reaches the maximum channel utilization at input traffic 0.2 while IEEE 802.11 MAC at input traffic 0.8. The channel utilization of IEEE 802.11 MAC is 58 percent in networks with ARLs. Normally the channel utilization of IEEE 802.11 MAC is about 80 percent at full load if ARL or MHS problems are not considered [6]. As there is no MHS in this simulation scenario, only ARL problem is responsible for this 22 percent reduction of channel utilization. As CESFRA MAC solves ARL problem, it provides about 80 percent channel utilization. Figure 5-27 shows that CESFRA MAC reduces about 1 millisecond delay compared to IEEE 802.11 MAC when the input traffic is 0.8 or above. CESFRA MAC successfully transmits about 6000 more packets (See Figure 5-28), and thus it offers about 0.45 Mbps more throughput (See Figure 5-29) compared to IEEE 802.11 MAC in every 50 seconds simulation at input traffic 0.8 or above.

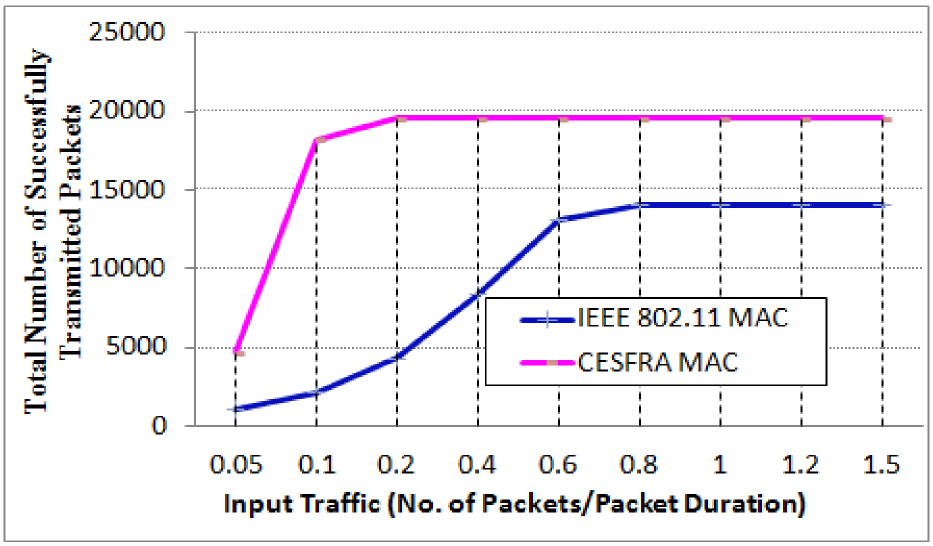


Figure 5-28: Effect of ARL problem on total number of packets.

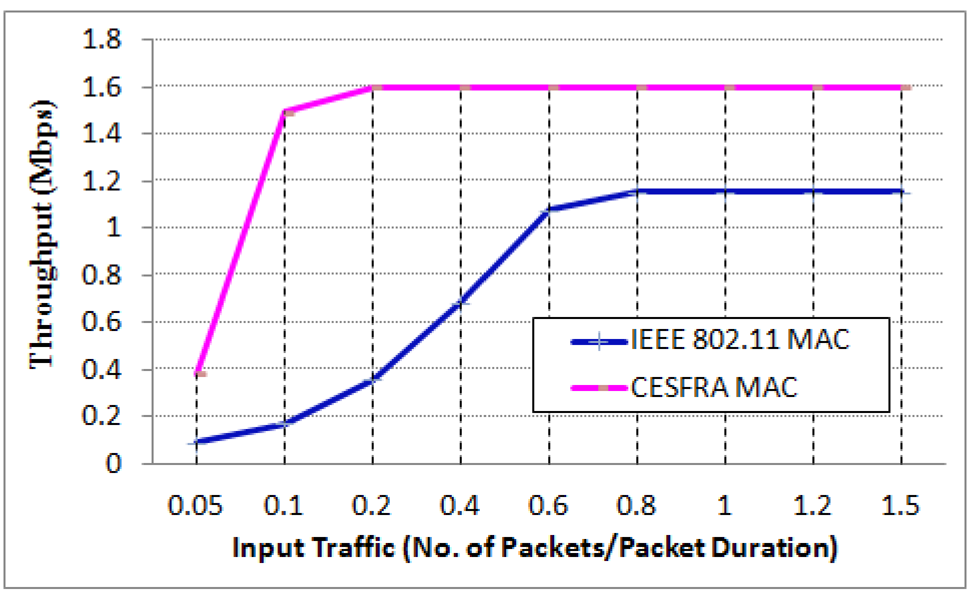


Figure 5-29: Effect of ARL problem on throughput.

The reservation based sliding frame mechanism in CESFRA MAC removes contention for channel access, collisions due to HS, MHS, and ARL problems, and thus helps more successful transmissions. On the other hand, contention, MHS, and ARL problems reduce IEEE 802.11's successful transmissions.

5.3.2 Markov Analysis of IEEE 802.11 Broadcast and CESFRA MAC Considering the Effect of Hidden Station and Mobile Hidden Station Problems in a DSRC/WAVE Based VANET Scenario

Hidden stations (HSs) and mobile hidden stations (MHSs) are very common in vehicular communications. Vehicles running in both directions in a highway may turn into HSs. Figure 5-30 illustrates a highway scenario where all the vehicles are randomly broadcasting basic safety messages (BSMs) every 100 ms. Let us consider a snapshot where Vehicle u is broadcasting a periodic basic safety message to the vehicles (i.e. k, h, f, etc.) in its transmission range. At this situation, a, b, c, etc. are HSs to u, because they are also broadcasting the periodic basic safety messages. As a does not have any knowledge of u's transmission and vice versa, the basic safety messages collide at f.

All the vehicles coming from the opposite direction in the other side of the highway are MHSs to each other. For example, u and m are MHSs to each other, because after a while they will have some common receivers (i.e. f, g, etc.). As they are broadcasting their basic safety messages without the knowledge of the transmission of one another, their transmissions collide at f. Although one MHS is enough to make a collision, there might have several MHSs colliding with the same transmission. The severity of MHSs can be measured probabilistically. The severity of having interfering MHSs in a highway scenario as shown in Figure 5-30 is calculated by discrete time Markov chain (DTMC) for both CESFRA MAC and IEEE 802.11 Broadcast.

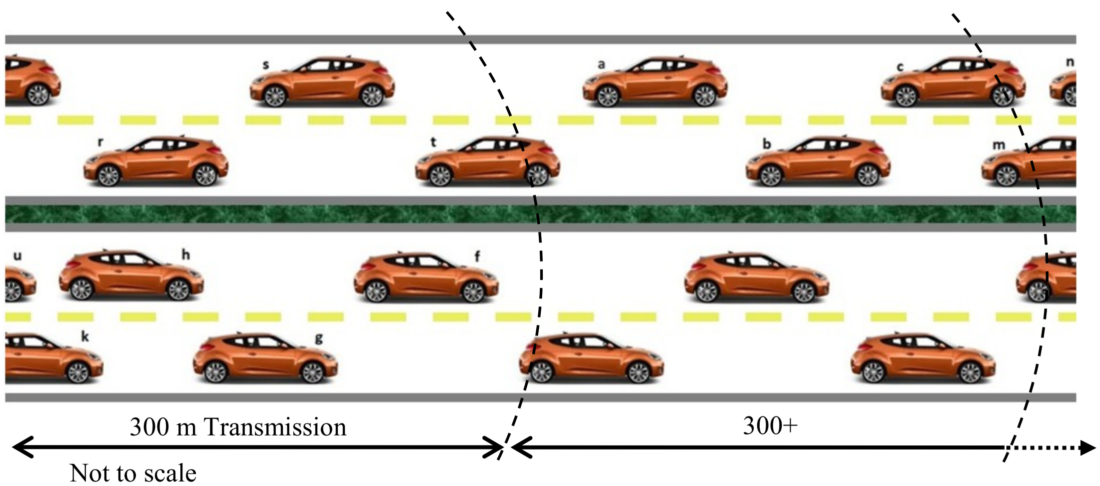
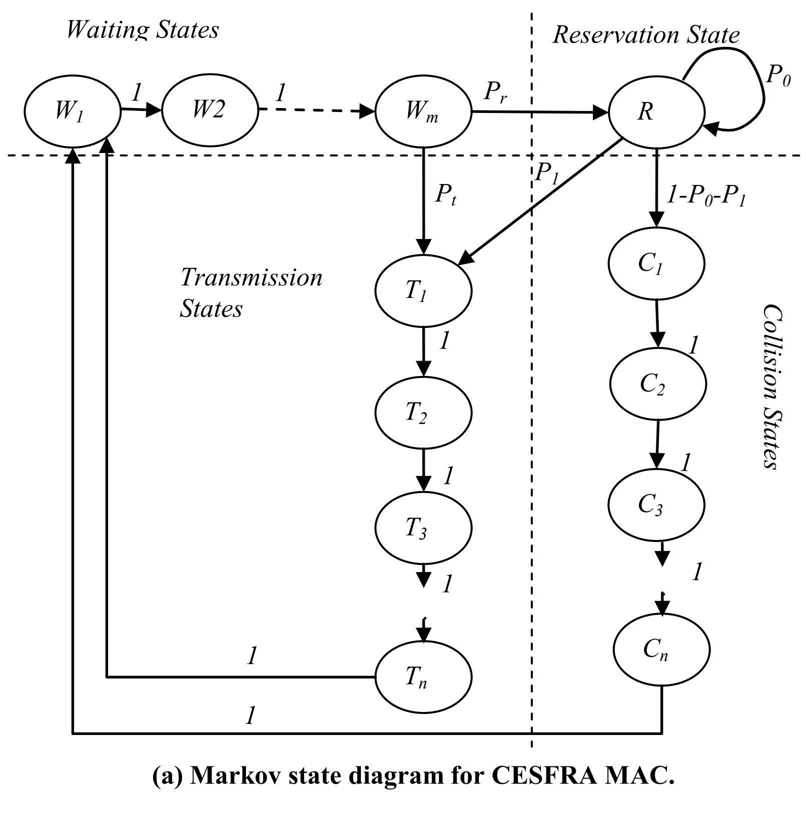


Figure 5-30: HSs and MHSs in a DSRC/WAVE based highway scenario.

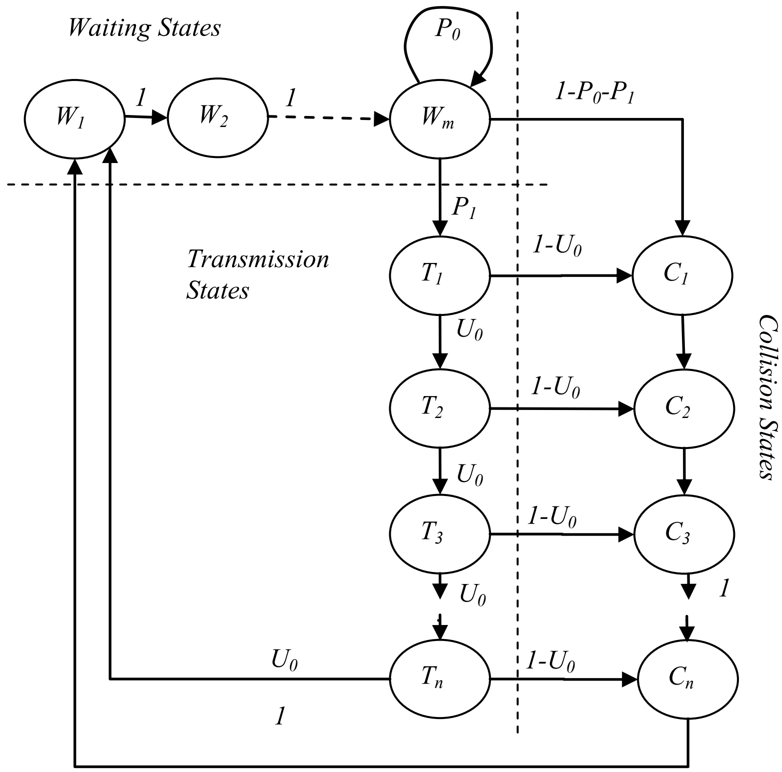
5.3.2.1 Discrete Time Markov Chain Model for CESFRA MAC for DSRC/WAVE Highway Communication Scenario

According to the principle of CESFRA MAC, the time channel in divided into frames, and the frames are divided into slots. Each station reserves a slot for couple of subsequent frames. The slot reservation is maintained or corrected by the status information obtained from CIs. The usages of CIs eliminate both HS and MHS problems. In this Markov model, each station can be in either one of the following four states: waiting, reservation, transmission and collision. Waiting state represents the probability of a station to be in waiting period (i.e. 100 ms according to DSRC/WAVE based systems) between the subsequent BSMs transmissions. Reservation state represents the probability of a station to be in the initial reservation process. I am considering that N is an average number of equal priority stations who are initially contending for one slot reservation, and all of these stations are in one contention region. After that the reservation is controlled by CIs. I am also considering that N_h is an average number of hidden and mobile hidden stations who may be responsible for MAC collisions. States of the Markov chain represent the states of a station using CESFRA MAC. The duration of one Markov chain time step is considered equal to the time required for sensing the channel and reserving a slot. Propagation delays are very small, and they are ignored. Let us consider n Markov time steps are required to transmit data from one station, and a station requires to exhibits m waiting states where, $m = 100\, ms/Markov\ step$. The probability that an idle station attempts to send a packet during a Markov time step is a. The probability that k stations attempt a transmission during a given slot is given by

$$q_k = C_k^N a^k (1-a)^{N-k} \quad . \tag{5.3.1}$$



(a) Markov state diagram for CESFRA MAC.



(b) Markov state diagram for IEEE 802.11 Broadcast.

Figure 5-31: Markov state diagrams CESFRA MAC and IEEE 802.11.

Figure 5-31(a) shows the state transition diagram of CESFRA MAC. R represents the reservation state where the channel is sensed and a slot is reserved for starting a communication. If the channel is sensed busy, a station will remain in the reservation state with transition probability, P_0 which means a station will not request to access the channel. P_0 is calculated from Equation (5.2.15) and given by

$$P_0 = (1-a)^N \; . \qquad \textbf{(5.3.2)}$$

If the channel is sensed idle, a station reserves a slot, and starts transmission using that slot. At this moment, the station moves from the reservation state, R to the transmission state, T_1 with transition probability P_1 which is the probability that only one station gets access to any slot for reservation and transmission. The transition probability P_1 is calculated using Equation (5.2.15) and given by

$$P_1 = Na(1-a)^{N-1} \; . \qquad \textbf{(5.3.3)}$$

A station must exhibit n transmission states (i.e. T_1, T_2, ..., and T_n). with transition probability one to transmit a packet. CESFRA MAC is aware of HSs and MHSs, this is why the transmission states are not affected by any collision. If two or more stations reserve the same slot simultaneously, a station must move from the reservation state, R to the collision state, C_1 with transition probability, $(1 - P_0 - P_1)$. Whenever there is a collision, the whole packet is lost. This is why every transmission state has a corresponding collision state, any station who enters the first collision state, C_1 must have to exhibit all the remaining collision states (i.e. C_2, C_3, ..., and C_n) with transition probability, one. W_1, W_2, ..., W_m are waiting states. A station in either T_n or C_n state must move to the first waiting state, W_1 with transition probability one. Whenever a station enters W_1 state, it must exhibit all the waiting states with transition probabilities one. As a slot is reserved by a station, it can reuse the slot. This is why, whenever a station reaches the last waiting state, W_m, it must start transmitting the next packet and moves to the first transmission state, T_1 with high transition probability, P_t. A station may need to make a new reservation of slot for any unexpected collision. In this case, the station changes its state from W_m to R with transition probability P_r which is given by $(1 - P_t)$. I create a state transition matrix, **P,** with all the transition probabilities given by the state diagram in Figure 5-31(a). I organize the distribution vector at equilibrium as follows,

$$\pi = [W_1 \quad W_2 \quad . \quad . \quad W_m \quad R \quad T_1 \quad T_2 \quad . \quad . \quad T_n \quad C_1 \quad C_2 \quad . \quad . \quad C_n]^T . \qquad \textbf{(5.3.4)}$$

At equilibrium, the distribution vector is obtained by solving following two equations,

$$\mathrm{P}\ \pi = \pi , \qquad \textbf{(5.3.5)}$$

and

$$\sum \pi = 1 . \qquad \textbf{(5.3.6)}$$

The solutions of Equations (5.3.5) and (5.3.6) are given by

$$W_1 = W_2 = .. = W_m = \frac{1}{A_1} , \qquad \textbf{(5.3.7)}$$

$$R = \frac{P_r}{A_1(1 - P_0)} , \qquad \textbf{(5.3.8)}$$

$$T_1 = T_2 = ... = T_n = \left(P_t + \frac{P_1 P_r}{1 - P_0} \right) \times \frac{1}{A_1} \qquad \textbf{(5.3.9)}$$

and

$$C_1 = C_2 = ... = C_n = P_r \frac{1 - P_0 - P_1}{(1 - P_0) A_1} , \qquad \textbf{(5.3.10)}$$

where,

$$A_1 = m + \frac{P_r}{1-P_0} + n\left(P_t + \frac{P_1 P_r}{1-P_0}\right) + n\ P_r \frac{1-P_0-P_1}{1-P_0}. \quad \textbf{(5.3.11)}$$

A Markov model of CESFRA MAC is designed and the state probabilities are calculated in this sub-section. The Markov model of IEEE 802.11 Broadcast is presented in the next sub-section.

5.3.2.2 Discrete Time Markov Chain Model for IEEE 802.11 Broadcast Considering HS and MHS Problems

IEEE 802.11 is one of the widely used MAC protocols for wireless access, and IEEE 802.11 Broadcast is considered for vehicle to vehicle communication under the new standardization process of IEEE 802.11p specially for vehicle to vehicle broadcasting. That is why it is important to investigate how IEEE 802.11 Broadcast behaves with the HS and MHS problems in a highway traffic as shown in Figure 5-30. A Markov model of IEEE 802.11 Broadcast for DSRC/WAVE based systems is designed in this sub-section. This is used as a benchmark for the Markov model of CESFRA MAC described above.

Let us assume that there are N equal priority stations that contend for a channel access. The duration of one Markov time step is considered equal to the time it takes a station to sense the presence of a carrier plus the distributed inter frame space (DIFS) time, and one frame transmission takes several Markov chain time steps. Let, n Markov chain time steps are required to transmit one frame.

A station using IEEE 802.11 Broadcast may be in one of three states: waiting, transmission and collision. Waiting state represents the probability of a station to be in the time (i.e. 100 ms according to DSRC/WAVE systems) between two consecutive broadcasts. Let a station requires to exhibit m waiting states where, $m = 100\ ms/one\ Markov\ step$. The waiting states are W_1, W_2, ..., and W_m. If a station enters the first waiting state, W_1, it must exhibit all the waiting states through W_m. This is why, the transition probability from one waiting state to another waiting state is always one. The state of a station changes from W_m to any of the other two states (i.e. T_1 or C_1) if the station has frames to transmit. If a station does not have frames to transmit, it remains in the last waiting state, W_m with transition probability, P_0 as calculated in Equation (5.3.2). If a station has frames to send, and if it starts its transmission successfully, it's status changes to the first transmission state, T_1 with transition probability, P_1 as calculated in Equation (5.3.3). If more than one station transmit simultaneously, the state of a station changes to the first collision state, C_1 with transition probability, $(1 - P_0 - P_1)$. There are n number of transmission states (i.e. T_1, T_2, ..., and T_n) as shown in Figure 5-31(b), and each transmission has a corresponding collision state (i.e. C_1, C_2, ..., and C_n). Since IEEE 802.11 Broadcast is not aware of HSs or MHSs, there is a possibility of collision in all the transmission states. If there is no collision by HSs and MHSs, the state of a station changes to the next consecutive transmission state with transition probability, U_0 and finally moves to the first waiting state, W_1 with transition probability, U_0. U_0 is defined as the probability that no HSs and MHSs are transmitting. If total number of HSs and MHSs is N_h, U_0 can be calculated using Equation (5.2.15) and given by

$$U_0 = (1-a)^{N_h}. \quad \textbf{(5.3.12)}$$

The probability that one or more HSs and MHSs are transmitting simultaneously is $(1 - U_0)$. Hence, for a collision due to HSs or MHSs in any of the transmission states, the state of a station changes to the corresponding collision state with transition probability, $(1 - U_0)$ as shown in Figure 5-31(b), and must changes to the first waiting state, W_1 after exhibiting the rest of the collision state with transition probability one.

A state transition matrix, **P**, can be obtained with the transition probabilities given by the state diagram in Figure 5-31(b). The state distribution vector, π , is in the following from:

$$\pi = \begin{bmatrix} W_1 & W_2 & . & . & W_m & T_1 & T_2 & . & . & T_n & C_1 & C_2 & . & . & C_n \end{bmatrix}^T . \quad \textbf{(5.3.13)}$$

At the equilibrium, the distribution vector is obtained by solving the following equations:

$$\mathrm{P}\ \pi = \pi , \quad \textbf{(5.3.14)}$$

and

$$\sum \pi = 1 . \quad \textbf{(5.3.15)}$$

The solution of Equations (5.3.14) and (5.3.15) gives

$$W_1 = W_2 = ... = W_{m-1} = \frac{1}{A_2} \ , \quad \textbf{(5.3.16)}$$

$$W_m = \frac{1}{(1-P_0)A_2} \quad \textbf{(5.3.17)}$$

$$T_n = \frac{1}{A_2} \times \sum_{k=1}^{n} \frac{P_1 U_0^{k-1}}{1-P_0}, \quad \textbf{(5.3.18)}$$

and

$$C_n = \frac{1}{A_2} \times \left(\frac{n(1-P_0-P_1)}{1-P_0} + \sum_{k=1}^{n} \sum_{v=1}^{k} \frac{P_1(1-U_0)U_0^{v-1}}{1-P_0} \right), \quad \textbf{(5.3.19)}$$

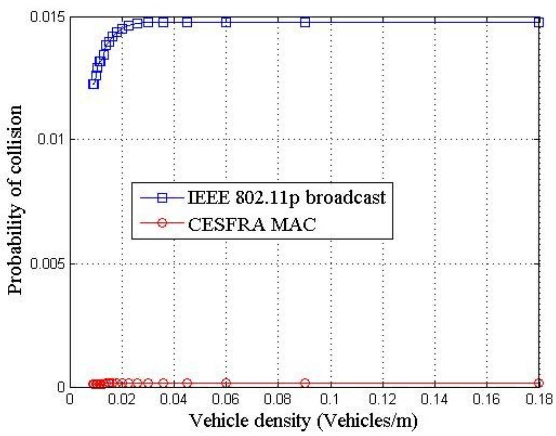
where,

$$A_2 = (m-1) + \frac{1}{1-P_0} + \sum_{k=1}^{n} \frac{P_1 U_0^{k-1}}{1-P_0} + \frac{n(1-P_0-P_1)}{1-P_0} + \sum_{k=1}^{n} \sum_{v=1}^{k} \frac{P_1(1-U_0)U_0^{v-1}}{1-P_0} . \quad \textbf{(5.3.20)}$$

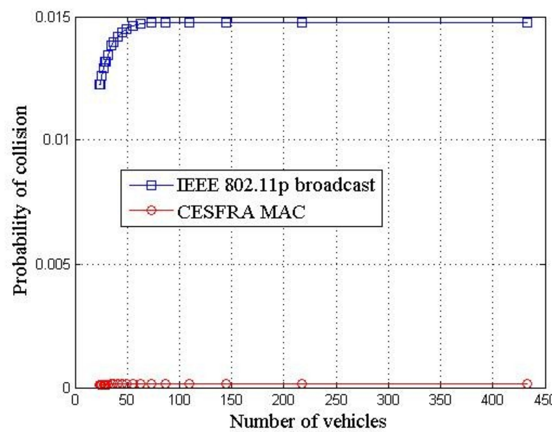
Using these two models, the probability of collision due to HSs and MHSs in vehicle to vehicle communication is calculated using MATLAB.

Table 1: Values used in Markov analysis.

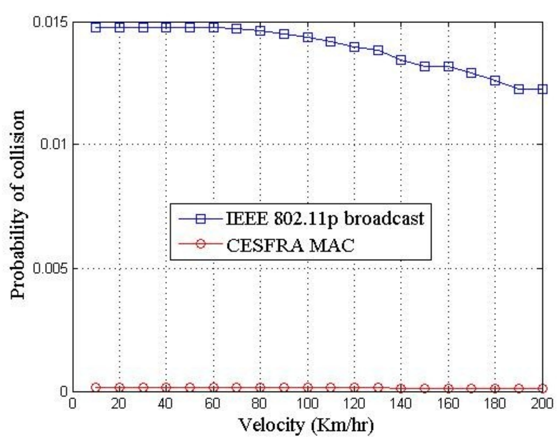
Parameter Name	Value
Packet length	512 Byte
Bit rate	3 Mbps
Safety message interval	100 ms
Breaking time	2 sec
Transmission range	300 m
Number of lanes	2
Probability of transmission	0.2



(a)



(b)



(c)

Figure 5-32: Effect of HSs and MHSs in DSRC/WAVE systems.

A highway scenario as shown in Figure 5-30, where all the vehicles have the same velocity, is considered for this Markov analysis. Figure 5-32(a), (b) and (c) illustrate the effect of HSs and MHSs in DSRC/WAVE based VANETs with respect to vehicle density, number of vehicles in the collision region and velocity of the vehicles on the highway. Vehicle density is considered same all over the highway. The collision region is defined as the region around the transmitter within which a transmitted packet has the possibility to be collided. The values of the parameters used in this Markov analysis are included in Table 1. The probability of collision while using IEEE 802.11p broadcast is about 0.0125 (i.e. 1.25%) for a vehicle density 0.01 vehicles/meter or for about 25 vehicles in the collision region in a two lane highway as shown in Figure 5-32(a) and (b) respectively. The probability of collision increases with the increment of the vehicle density, and it is about 0.015 (i.e. 1.5%) for vehicle density 0.03 or for number of vehicles 75. For high vehicle density the probability of successful transmission (i.e. P_1 in Figure 5-32(a)) is very low. In these cases, a station changes its state from W_m to C_1 with transition probability $(1 - P_0 - P_1)$ which is approximately one. This is why, the increment of the probability of collision is very low for the vehicle density greater than 0.03, and it is almost constant at about 0.015 for higher vehicle densities or higher number of vehicles in the collision region. On the other hand, the reservation mechanism of CESFRA MAC removes the contending behavior of channel accessing. This is why, the probability of collision for CESFRA MAC is approximately zero. Provided that the probability to be in the waiting states is very high for maintaining the DSRC/WAVE specification of 100 ms waiting time between consecutive message transmissions. Apparently, 1.5% packet loss using IEEE 802.11p broadcast is not a significant figure for a packet communication system other than VANETs with safety messaging. Because, DSRC/WAVE based VANETs are aimed to disseminate safety critical information, 1.5 packets loss (i.e. actually 2 packets, if part of a packet is collided, the whole packet will be lost) out of 100 packets is meaningful. High speed vehicles require more safe breaking distance (i.e. 2 second breaking time is used as shown in Table 1). Figure 5-32(c) shows that the low speed traffic is affected by HS and MHS collisions more than the high speed traffic.

The next sub-section contains more analysis of the severity of the ARL problem in VANET. It is explained how CESFRA manages to solve this problem with its cross-layer behavior.

5.3.3 Justification of the Cross Layer Behavior of CESFRA in the DSRC/WAVE Systems

CESFRA promises an efficient information dissemination in the WAVE/DSRC systems. The IEEE P1609 standards define the communication services in different layers of the WAVE/DSRC systems. P1609.1, P1609.2, P1609.3 and P1609.4 represents WAVE resource manager, WAVE security services, WAVE networking services and WAVE multi-channel operations (i.e. DSRC) respectively [65]. The SAE J2735 DSRC message set dictionary (MSD) defines the application level message that are exchanged [62] in the DSRC/WAVE systems. According to SAE J2735, all the messages are broadly divided into three types based on application e.g. basic safety message (BSM), roadside alert message and probe vehicle message [62]. According to [62] all vehicles must transmit basic safety messages every 100 ms. DSRC/WAVE systems have mobility related problem (i.e. MHS problem [6]), and ARL problem. In this section, I have explained these problems using different DSRC/WAVE based scenario, and analyzed how my cross-layer based algorithm confirms better results.

5.3.3.1 Cooperative Collision Warning/Avoidance in DSRC/WAVE Systems with CESFRA

The on-board unit (OBU) collects safety critical information from the messages broadcast by surrounding vehicles, and warns the driver if a collision is likely. The control channel with a transmission range of 300 m is used for this kind of messaging. An example scenario is presented in Figure 5-33. If Vehicle V8 is stopped suddenly for any reason (i.e. a blockade on the road, snow, a collision already happened etc.), the vehicles within 300 meter of V8 is supposed to get the message from V8, and they will either try to change lane or stop. In a high speed and high traffic scenario, in most of the cases failure to change lane or stop within 300 meter will cause disastrous back to back collision. CESFRA solves this problem disseminating this collision avoidance information up to 900 meter without any routing.

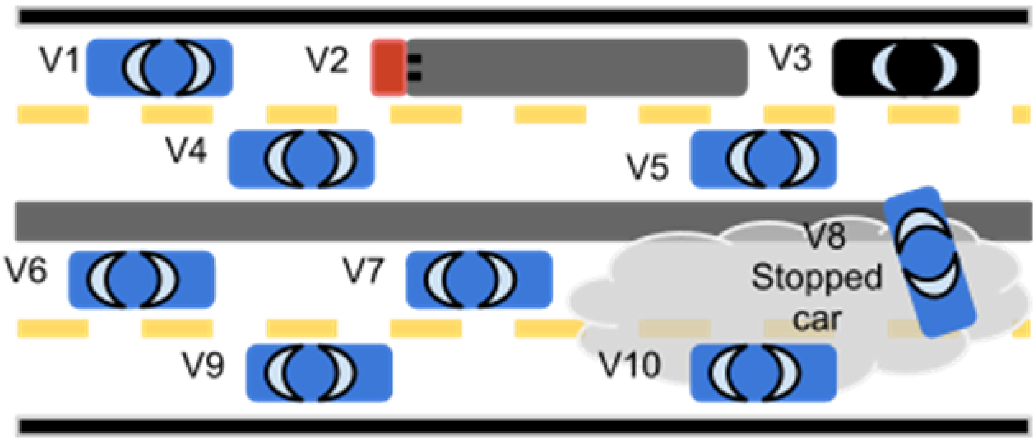


Figure 5-33: Cooperative collision warning with CESFRA.

5.3.3.2 Shadowing Effect and Asymmetric Radio Link Problem

Asymmetric radio link can also be generated by blocking of a big vehicle. Figure 5-33 illustrate a scenario how an ARL problem may occur by a big truck. A big truck V2 in Figure 5-33 may be a reason of asymmetric radio link to the car V3 just behind it. If the V1 suddenly brakes for any reason, the car behind the truck cannot listen the signal although it is in the transmission range of V1. So, the car behind the truck collides with the truck. CESFRA in VANET solves this problem. This ARL scenario are discussed elaborately in the next sub-sections.

5.3.3.3 Emergency Vehicle Warning - an Example ARL Scenario

An emergency vehicle (i.e. Vm in Figure 5-34) transmits its approaching message in a range of 1000 meter as mentioned in DSRC standards. Other vehicles are transmitting with 300 meter range. So, the vehicles in the scenario are affected by the ARL problem. Suppose, Vehicle V1 has sent a safety critical message to Vehicle V2, and emergency Vehicle Vm is approaching towards V1 and V2. Vm is HS or MHS to V1, and there is a packet collision at V2. So, V2 is losing packets from both V1 (i.e. safety critical message packet) and Vm (i.e. emergency vehicle approaching alert message packet). This problem is not solved by DSRC MAC (i.e. IEEE 802.11p) or any other distributed MAC [6]. According to the scenario Vehicle V2 is the last vehicle in 1000 meter which receives emergency vehicle warning message. CESFRA can disseminate this information to V1, V5 and so on with it routing-less controlled broadcasting behavior. CESFRA can do the same even if the emergency vehicle transmission range is limited to 300 meter as other vehicles.

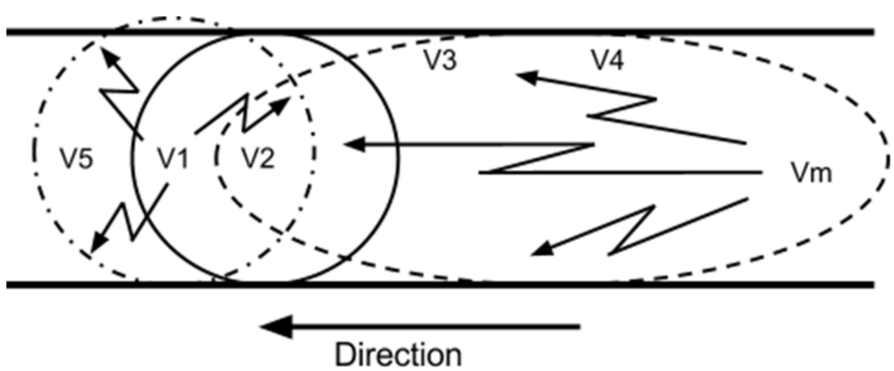


Figure 5-34: Asymmetric radio link problem in a DSRC/WAVE systems based scenario with emergency vehicle.

5.3.3.4 Service - Toll Collection and Work Zone Warning - an Example ARL Scenario

Another DSRC scenario of ARL problem arises when the transmission power of a service channel is varied to support services using different transmission ranges. Figure 5-35 shows that Vehicles V8 and V10 are in toll collection service, and they are using about 10 ~ 90 meter range; work zone RSU and road condition warning RSU are communicating with 90 ~ 300 meter range; whereas other vehicles (i.e. V6, V7, V9, V11 and V12) are transmitting BSMs with 300 meter range). BSMs from V7 and V9 are making ARLs with V8 and V10. CESFRA solves this problem with its cross-layer sliding frame behavior. V8 and V10 know in advance about the toll collection communication of V7 and V9 with the toll collection RSU.

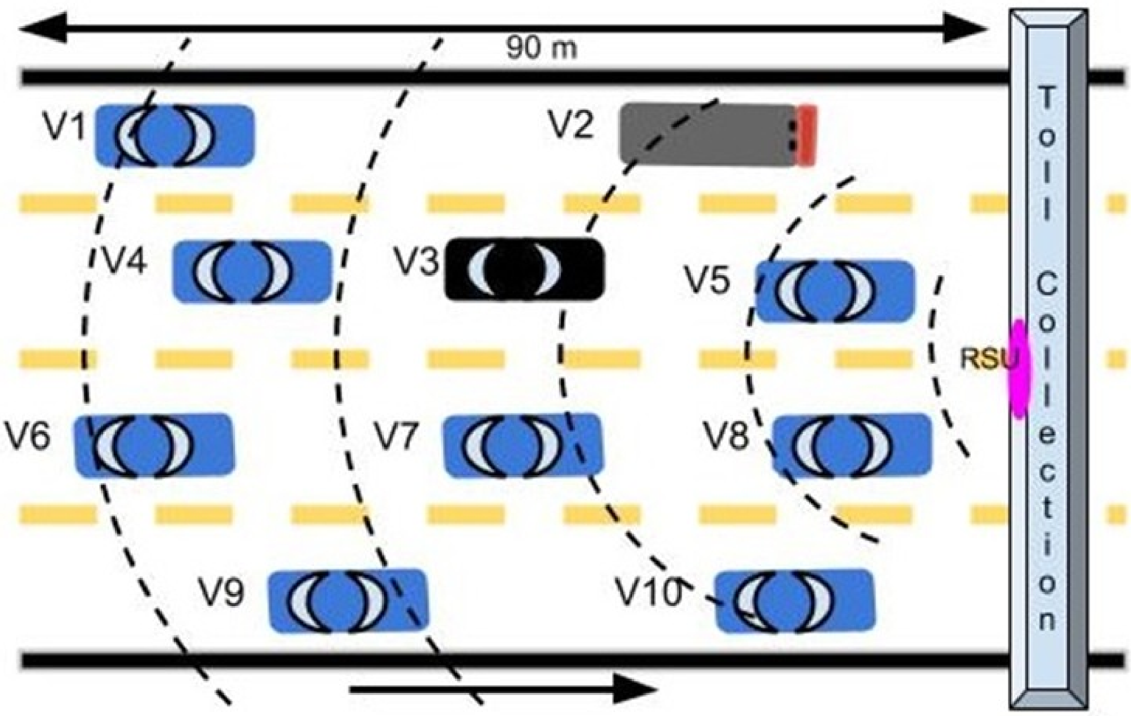


Figure 5-35: Toll-collection scenario in DSRC/WAVE systems.

CESFRA also improves the quality of service of the toll collection service. According to the DSRC/WAVE design, vehicles are allowed to run in normal speed on highway while collecting toll by toll collection RSU. How much time an RSU will get to collect the toll any vehicle depends on the number of vehicles within its 90 meter range. CESFRA introduces any vehicle with the toll collection RSU at least 3 hops ahead which means when a vehicle is at least 270 (i.e. 90 meters X 3 hops) meters apart. So, CESFRA makes toll collection procedure smooth and reliable.

CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1 Conclusion

The network layer communication and multiple access procedures in ad hoc networks are not error prone till now, although significant research has been done in network and MAC layers. This is why, this thesis is organized to address one network layer issue and several MAC layer issues. A new approach to reduce packet loss due to inevitable link failures in MANET is presented in this thesis. The proposed algorithm is implemented in DSR, but this algorithm is independent of the choice of any on-demand routing protocol. RLT is estimated using the route discovery mechanism. Using RLT and latency, the number of packets that can traverse a route is estimated, and only this number of packets is sent through that route. The simulation results show that packet loss decreases and packet delivery ratio increases significantly compared to the conventional DSR and DSR with direction tracking if this algorithm is applied to DSR.

The MAC layer issues e.g. hidden station, mobile hidden station, neighborhood capture and asymmetric radio link problems are particular points of attention in this thesis. IEEE 802.11 solves HS and ES problems, but does not solve neighborhood capture, mobile hidden station and asymmetric radio link problems. The proposed reservation based ERA solves HS and ES problems, and significantly mitigates NC and MHS problems by reducing the probability of their occurrence in the network. If all the stations use IEEE 802.11 as a MAC protocol, at least two stations hidden to each other may block their common neighbor for an indefinite span of time. This blocking gets more severe when number of stations gets larger. ERA MAC protocol provides a good channel accessing probability to the blocked station even if the number of the neighbors of the blocked station is more than two. ERA reduces collisions due to MHSs, and thereby provides good chances of successful transmissions. The analysis of another reservation based protocol called SFRA shows that it behaves similarly as ERA to the above mentioned problems. Both ERA and SFRA outperforms IEEE 802.11 and demonstrates that the reservation based MAC protocols like ERA and SFRA better suits in mobile networks. It is very encouraging that both ERA and SFRA achieves about 90 percent successful transmissions rate when there is 1 MHS, and it decreases significantly when the number of MHSs increases. In another investigation, it is found that both ERA and SFRA reduce the collisions due to the ARL problem, and the probability of collision significantly degrades the channel utilization for high traffic, whereas the distributed protocols like IEEE 802.11 do not address the ARL problem. That is why, I proposed another MAC protocol called ESFRA which solves the MHS and ARL problems in addition to the NC, HS and ES problems. ESFRA provides a solution to MHSs by including the relative positions of the transmitting stations in three hop neighborhood. Markov modeling that includes MHSs is developed for ESFRA, as well as SFRA and IEEE 802.11. The Markov models developed here are used to calculate the performance figures of ESFRA, SFRA and IEEE 802.11. Based on the Markov modeling, ESFRA provides lower collision probabilities, higher throughputs and lower delays compared to SFRA and IEEE 802.11. While development of VANETs and works on IEEE 802.11p are continuing, MAC protocols for these networks must be designed to handle MHSs, ARLs as well as other MAC problems. ESFRA like protocols can provide competitive solutions. The only requirement for ESFRA is to have synchronization between mobile nodes, with the availability of positioning systems, like GPS. If this synchronization problem can be solved relatively reliably, it will remove the main obstacle in the implementation of ESFRA in practical systems.

The DSRC/WAVE systems disseminate safety critical information using IEEE 802.11p broadcast as a MAC protocol. Studies show that IEEE 802.11p does not address the adverse effects of asymmetric radio link and mobility related problems in VANETs. The discussion in this paper emphasizes the solution to these problems by incorporating some interactions between subsequent layers. A cross-layer based MAC algorithm called CESFRA is presented in this thesis. CESFRA is based on ESFRA and designed for a specific application, VANET. It disseminates the network layer information up to 3rd hop with its sliding frame mechanism. Thus it confirms routing packets up to 3rd hop in the network which can be considered a layer 2 routing. The analysis in Chapter 5 shows that it solves the MHS and ARL problems in DSRC/WAVE systems with its routing less behavior up to 3rd hop. Markov analysis and simulation studies in OMNeT++ show that CESFRA MAC outperforms IEEE 802.11p broadcast and IEEE 802.11 MAC in resolving the contentions and collisions due to mobility and other factors. CESFRA MAC offers about eighty percent channel utilization and low average packet delay (i.e. about 2 millisecond) which is very low compared to minimum human response time (i.e. 200 millisecond) required after any critical events (i.e. accidents, emergency brakes etc.). So, CESFRA can be a good candidate for safety critical information dissemination in DSRC/WAVE or any other similar systems.

6.2 Future Work

There are some factors which are assumed perfect or overlooked throughout this analysis. Those are time synchronization among the mobile vehicles, size of the collision domain, privacy issues and security issues in vehicular communication.

6.2.1 Time Synchronization Among the Mobile Vehicles

One of the basic criteria in designing ESFRA and CESFRA is that the mobile stations/vehicles must have to be synchronized with respect to time. Throughout this research, I considered that all the mobile stations/vehicles are synchronized with respect to time. There is a scope of research how the mobile stations/vehicles can be time synchronized in the back-end.

6.2.2 Size of the Contention Domain

In wireless communication, collision domain is an approximate bounded area in which a receiver has the probability to receive multiple packets simultaneously in the same frequency channel. For an Ad hoc network with static stations/nodes, it is bounded by the transmission area of a node considering symmetric transmission ranges. The collision domain is bigger if asymmetric transmission ranges as well as mobility of stations/vehicles are considered. The stations contends for the channel to get rid of the collisions supposed to occur in the collision domain. For an Ad hoc network with symmetric transmission ranges as well as static stations, the contention domain is two hops. So most of the MAC protocols designed for this kind of Ad hoc networks use a two-hop contention domain. If the nodes are mobile and the transmission ranges are considered asymmetric, the contention domain is three hops. Because ESFRA and CESFRA address the MHS and ARL problems, the design of ESFRA and CESFRA is based on a three-hop contention domain. So, CESFRA is enlarging the contention domain to solve the MHS and ARL problems. There is a scope of research here, how this changes to contention domain is affecting the performance, and how can we optimize it.

6.2.3 Privacy and Security Issues

The privacy and security issues are not in the scope of this research. The privacy and security issues are important factors. Because vehicular wireless communications are based on concept of cooperation with one another, the vehicle users are required to share identifications (i.e. MAC addresses), location information, speeds, different sensor outputs etc. which affect the privacy and security issues. So, there is a scope of research here how these issues can be solved without violating the requirements of cooperation.

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Conference Proceedings: Computers & Informatics (ISCI), 2011 IEEE Symposium on

Author: Rahman, K.A.; Shazzad, K.; Tepe, K.E.

Publisher: IEEE

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Author: Rahman, K.A.; Rahman, K.A.; Lott, M.; Tepe, K.E.

Publisher: IEEE

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