POWER CONTROL FOR FAIR DYNAMIC CHANNEL RESERVATION

BY

PARISA HAGHANI

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical and Computer Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2011

Urbana, Illinois

Adviser:

Assistant Professor Yih-Chun Hu

ABSTRACT

Providing safety applications is one of the principal motivations behind deploying vehicular ad hoc networks (VANETs), where each vehicle is equipped with a wireless transmitter and receiver. These applications require fair (i.e., all vehicles get equal fraction of time allocation for their transmissions) and reliable (i.e., transmissions are received with high probably by the intended receivers) broadcasting of relevant driving data, such as position, speed and direction of a vehicle. In this thesis we compare the performance of IEEE 802.11p and a recent time-division based medium access control protocol, Dynamic Channel Reservation (DCR) in realistic high-density traffic scenarios. We focus on the communication requirements that allow vehicles to receive safety messages well enough in advance to warn the driver in a timely manner and avoid crashes. We observe performance degradation in both schemes as we examine them in congested environments. Previous work confirms our observation on the performance of 802.11p. In DCR, on the other hand, some vehicles may face starvation (i.e., they do not get a chance to transmit in a long time) in dense scenarios, where all channels have been pre-reserved by other vehicles. In order to avoid this situation, we propose a modified version of DCR, *fDCR*, in which channels can be occupied by several vehicles, thus fostering a fair channel reservation scheme. Our channel reservation scheme is designed in a way that minimizes packet collisions when transmitter and receiver are close to each other. Furthermore, to enhance the probability of reception in nearby vehicles, which is one of the main communication requirements of safety applications, we propose a low-overhead transmission power control scheme. Our fully distributed power control scheme leverages on the extra transmitted information by DCR to estimate the number of vehicles in its transmission range, and accordingly adjust the transmission power. Experimental results show significant performance gains in cases of both cross-through and non-cross-through traffic for our proposed scheme in

comparison with 802.11p.

To Saman, for his love and support.

ACKNOWLEDGMENTS

I would like to sincerely thank my adviser, Yih-Chun Hu, for giving me the opportunity to pursue this thesis under his supervision. He introduced me to this exciting area of research, and guided me throughout the course of my studies at UIUC. I have learned a great deal from him, both academically and personally. I am also indebted to him for supporting my career and life choices with invaluable advice.

I thank Ray Kong Lam for providing me with his implementation code of DCR and patiently answering my questions regarding it. I would also like to thank the members of our lab who made my stay at UIUC more pleasant and memorable. Special thanks go to my office mate, Danesh, with whom I had a lot of interesting discussions.

I am grateful to my parents for their never-ending love and support. They have been great sources of inspiration to me, and I would never stand where I am without them. I sincerely thank them. I thank Sasan and Laleh, for passing their valuable experience to me, and Sina, for our enjoyable talks.

And thank you Saman for always being there for me and encouraging me with your joyful smile. Your enthusiasm, liveliness, and creativity are a constant source of inspiration to me. I could not have completed this thesis without you, and I wholeheartedly thank you for all your love and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Improving road safety and reducing severe vehicle crashes are the main motivating forces behind intelligent transportation systems (ITS). These systems have identified ad hoc vehicular wireless communication as a key technology in building safety applications which aim at reducing the death toll due to vehicular accidents. Providing reliable communication is the principal requirement behind the usability of this technology in fostering safety applications. Safety applications require each vehicle to proactively broadcast periodic messages. These periodic one-hop messages, or so-called *beacons*, are used to establish mutual awareness to serve higher level applications such as cooperative collision warning, road hazard notification, and lane change assistance. Application designers require certain *quality of service* (QoS) in terms of packet reception probability, delay, and throughput to guarantee the effectiveness of their applications. For instance, a recent study [1] has identified some of the communication requirements for two specific applications, namely intersection crash avoidance, and pile-up collision avoidance. Furthermore, vehicular ad hoc networks (VANETs) are anticipated to be deployed in various urban scenarios. Therefore, it is essential to investigate the performance changes in different scenarios and their effects on the QoS required by higher application levels.

IEEE 802.11p has been standardized as the Medium Access Control (MAC) protocol to be used in VANETs. However, previous research [2, 3] has shown that the performance of 802.11p broadcast degrades in medium to high node density scenarios. This is mainly due to the *one-way* nature of 802.11p broadcasts. In wireless communication, a transmitter does not have a way of knowing if its transmission was successfully received by the receivers, unless they explicitly acknowledge the receipt of a packet. In broadcast, there are multiple potential receivers; thus, no ACK packets are sent back. The research community has proposed several metrics, such as vehicle traffic density [4] and channel load [5], which can be observed in the network in order to adjust communication behavior to varying node densities and situations. Transmission power, transmission rate, and packet size are elements which can be adjusted to meet the requirements of a dynamic environment and avoid causing congestion in 802.11p.

However, more recently, there have been attempts at designing new MAC protocols which suit the special characteristics of VANETs. Along this line of research, Lam and Kumar of [6] have tried to gain better performance by utilizing the specific *group behavior* structure of VANETs and designing a TDMA-based MAC protocol. They move from the random access nature of 802.11p to a more structured reservation-based method. Dynamic Channel Reservation (DCR), borrows techniques from ADHOC MAC [7] to build a VANET specific MAC protocol in which each vehicle is required to reserve a time channel and periodically transmit its packets in that channel. DCR has shown significant performance gains in comparison with 802.11, when utilized in moderate-density scenarios. In this thesis, we investigate the conditions under which vehicles can face starvation under DCR or performance degradation under 802.11. We use this insightful analysis to design a more flexible channel reservation scheme, *fDCR*, which permits multiple vehicles to transmit during the same time channel. Time channels are chosen such that when a channel is used by multiple vehicles, packet collisions are more likely to happen at distances farther from the transmitter. This design goal is based on observations made in a previous research paper [1], which show that specific safety applications, such as collision avoidance, require precise information from nearby vehicles, rather than from ones far away.

In congested scenarios, transmission power control is one of the main ways of limiting performance loss by decreasing the number of packet collisions. We propose a power control scheme which leverages the information transmitted in DCR used in channel reservation. This information allows each vehicle to decide whether its transmission power is causing congestion in other parts of the network, and adjust its power level accordingly.

As another important and frequent scenario which deserves special attention, we discuss the possible performance losses which can occur in DCR and 802.11 in cross-through traffic scenarios. Many crashes occur in the intersection of two roads as drivers fail to stop or yield, so safety applications can be effectively used in such situations to warn the drivers and prevent crashes. However, field experiments (e.g. [8]) show that radio wave propagation cannot be modeled solely based on the sender/receiver distance, but it also requires their categorization to as line-of-sight (LOS) or non-line-of-sight (NLOS) situations. We are interested to know how this difference in propagation affects the packet probability loss in 802.11 as well as DCR.

The rest of this thesis is organized as follows. Chapter 2 presents a discussion of related work in the area of congestion control in VANETs with an emphasis on power control schemes and an overview of the DCR medium access control scheme upon which our presented scheme is built. Chapter 3 discusses the system requirements to avoid starvation under DCR in high-density scenarios and, based on this analysis, presents fDCR and subsequently a transmission power control scheme in addition. Chapter 4 discusses the possible effects of cross-through traffic on both 802.11p and DCR. Chapter 5 presents experimental results, and finally Chapter 6 concludes the thesis.

CHAPTER 2

BACKGROUND AND RELATED WORK

The main goal in congestion control in VANETs is to ensure channel availability such that critical information can be transmitted on time and received with high probability. This critical information, or the so called *event-driven* messages, such as reports on a crash or warnings of getting too close to another vehicle, are produced utilizing periodic safety *beacons* which report the position, velocity, direction and other data related to a moving vehicle. These beacons should be transmitted often enough to ensure fresh data is used in higher-level applications which make critical decisions based on this data. On the other hand, these beacon transmissions can cause congestion and degrade the performance of underlying communication protocols, thus diminishing the effectiveness of these applications. Unlike beacons, event-driven messages are relayed, vehicle by vehicle, to spread awareness in a larger surrounding. The main question in controlling congestion with regard to event-driven messages is how to limit the number of relays to avoid the well-known *broadcast storm* problem [1] [9]. In the rest of the thesis, when we refer to congestion control, it is with regard to beacon messages and not event-driven messages.

There are three main ways to control congestion. First is by changing the beacon packet size. The smaller the packet is, the shorter the transmission time will be, and therefore channel busy time will also be reduced. However, VANET beacons require a fixed beacon packet size which includes all the necessary information for higher level decision making. The second adjustable factor is frequency. Again, this value is set to 10 beacons per second per vehicle to ensure the freshness of data. The third parameter is the transmission power, which directly affects the reception range of a transmission. We focus on this parameter for congestion control.

---

[1] A state in which a message that has been broadcast across a network results in even more broadcasts, and each broadcast results in still more broadcasts in a snowball effect.

The importance of controlling the transmission power in VANETs has been previously confirmed by a number of research papers on this topic. In [10] it is argued that the safety goals of a vehicular network are best achieved when *every* member of the network has a good estimation of the state, e.g., position, speed, and direction, of *all* vehicles in its surrounding. All vehicles in a certain area should restrict their transmission power by the same ratio in order to satisfy a maximum possible load on the wireless medium produced by periodic beacon transmissions. The fairness metric in this context is defined as maximizing the minimum transmission power of all vehicles under the constraint of limiting maximum load. The problem of ensuring fairness is defined as a min-max optimization problem and a centralized algorithm, called FPAV (Fair Power Adjustment for Vehicular Environments), is presented for achieving this goal [10]. Following the above concept of fairness, the authors in [11] present a distributed version of FPAV called D-FPAV (Distributed Fair Power Adjustment for Vehicular Environments). Each vehicle receives the state (e.g., position, speed, direction) of all other neighbors within its carrier sensing range at maximum power and locally computes a power assignment based on FPAV. In the next phase, the vehicles share their computed power assignments by broadcasting those values. Each vehicle chooses the minimum value it receives among all suggested power levels. It is shown that when the carrier sensing ranges of the vehicles are symmetric, D-FPAV reaches an optimal solution. For D-FPAV to be able to precisely compute power assignments, each vehicle is required to report its view of its surrounding (e.g., number of its neighbors and their positions) in a timely manner. This is done by piggybacking the aggregated status information once on every 10 beacon transmissions. The authors in [5] provide an analysis of the tradeoff between the effectiveness of controlling the channel load and the corresponding costs related to status updates of neighbors. Their approach reduces the overhead by having the vehicles transmit a histogram of neighbor positions instead of exact position information. This method effectively makes it possible to fix the beacon size (measured in kilobytes) as well, because the beacon size does not depend on the number of neighbors that each vehicle senses. Experimental results show that the optimal power levels can still be calculated with small errors.

In [12], each safety beacon is supposed to be accompanied by a specific distance range (e.g., 200 meters). The role of the power control algorithm is to ensure vehicles are not transmitting at excessive power that reaches beyond the specified distance range. Their approach is based on direct feedback. Each vehicle includes a list of loud vehicles, i.e., those which it received beacons from and which are outside the specified range, in its beacon. When a vehicle receives a beacon which includes itself in the list of loud vehicles, it lowers its transmission power level. This scheme is effective when beacons are not transmitted too often. In the case where beacons are required to be transmitted very often, the feedback beacon may not be heard by the loud vehicle, causing the loud vehicle to increase its power resulting in more packet loss (bipolar effect).

In contrast to the aforementioned systems which assume IEEE 802.11 is used as the MAC protocol, in this thesis, we are interested in designing a power control scheme for the DCR MAC protocol [6] which is a reservation-based scheme.

2.1 Overview of DCR

Dynamic Channel Reservation (DCR) [6] is a time-division MAC level protocol which aims at exploiting the special structure of vehicular networks to provide better application level QoS. In DCR, time is divided into periods of fixed duration called *multi-frames* which match the beaconing period of VANET applications. Each multi-frame is divided into a predefined number of *channels* (time slots). Using a procedure that we will describe in the following, each vehicle reserves a channel and broadcasts its beacon in this channel periodically. Therefore, unlike in 802.11p where a vehicle needs to contend for each packet to be transmitted, the vehicle only contends for a channel which repeats periodically (unless it has to give up its *owned* channel due to a reported collision). Channels can only be reused when there is enough spatial distance between their owners to avoid collisions. Figure 2.1 presents an example of channels and their reuse in a multi-lane road.

For DCR to work, each vehicle is required to maintain and periodically transmit two bitmaps of the size of the number of channels. We will explain how these bitmaps are used in the following paragraph. The first bitmap is the *channel availability bitmap* in which each vehicle maintains the status of the channels. Each time a vehicle receives a beacon from its neighbors in a

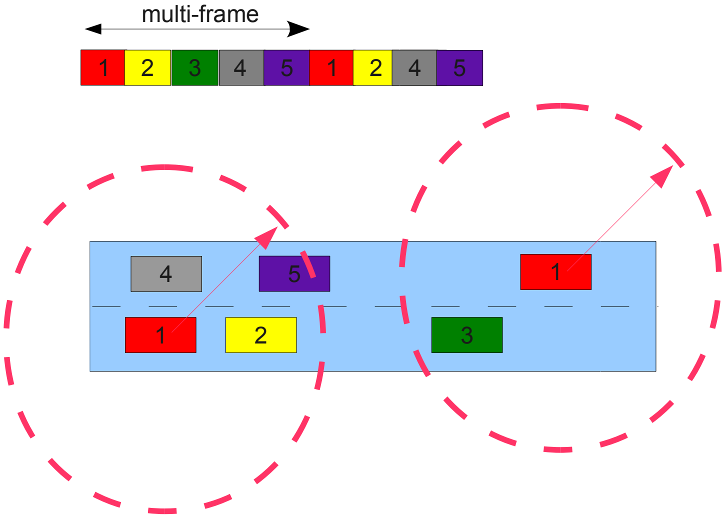


Figure 2.1: An illustration of channel allocation and spatial reuse in DCR. Vehicles' colors denote their channels. The red channel is repeating as there is enough spatial distance between the two vehicles to avoid the hidden terminal problem (they do not share common neighbors).

channel, it marks that channel as taken in the availability bitmap. It clears a channel's corresponding bit in the availability bitmap when it does not receive packets during that channel in three consecutive multi-frames. The second bitmap is used to detect packet collisions and is called the *channel collision bitmap*. Each vehicle monitors all channels and whenever it detects a collision, it marks the corresponding channel's bit in the collision bitmap as well as in the availability bitmap. These two bitmaps are piggybacked on each packet that a vehicle transmits.

The DCR protocol has two main procedures. First is the *channel contention procedure* in which a newly joined vehicle contends for a channel. The second procedure is the *collision detection and channel status change*, where a vehicle gives up its owned channel and repeats the contention procedure. It is assumed that vehicles are all completely time synchronized and are given the system parameters of the start time of multi-frames and number of channels in each multi-frame. Therefore, at each time instant, each vehicle is aware of the current channel. Upon joining the vehicular network, a new vehicle listens to the channel for several multi-frames and aggregates all information received from its nearby vehicles on the channel status by taking the union of the availability bitmaps it receives. A vehicle considers a channel to be *available* if it is not marked in the union of the received availability bitmaps, including the vehicle's own availability bitmap. It then chooses a channel uniformly at random among the available channels. Subsequently, the vehicle broadcasts a *probe* packet in the chosen channel time. If this packet does not cause collisions with any other transmissions, the vehicle will use this channel for future transmissions. Since collisions in a wireless medium cannot be detected by the sender, the vehicle uses information from the subsequently received collision bitmaps to decide whether its probe packet has caused a collision or not. It repeats the above procedure if at least one if its nearby vehicles reports a collision. Furthermore, collisions may happen when vehicles using the same channel move spatially too close to each other. If a vehicle detects collisions in its own channel, from the bitmaps it receives from its neighbors, in three consecutive multi-frames, it gives up its channel and begins the channel contention procedure. A vehicle following the above reservation-based protocol does not choose a channel which is reserved by its neighbors or neighbors of neighbors. Therefore, a vehicle's transmissions do not interfere with those of its neighbors or of its neighbors' neighbors. Therefore, the rate of packet collisions is very low in DCR.

DCR also provides a channel partitioning mechanism to manage two-way traffic. It dynamically divides the available channels into two non-overlapping sets to avoid packet collisions from vehicles coming in opposite directions. We refer interested readers to [13] which contains the details of this approach.

CHAPTER 3

HANDLING CONGESTION

As previously described, each vehicle in the DCR scheme reserves a channel and only transmits in that channel. If a vehicle is unable to reserve a channel, it will not transmit and will remain silent. When a vehicle does not get a chance to transmit for a long period of time, we say that vehicle is facing starvation. In this section, we investigate the requirements which should be met to allow for each vehicle to be able to reserve a channel and transmit periodically in that channel. In the following we use the terms channel and slot interchangeably.

We assume the payload (message) size is fixed (in safety applications a value of 200-500 bytes) and each vehicle is required to transmit with a frequency of 10 messages per second. With the above information and a known fixed data rate, the minimum required length of a time slot can be computed. The length of a multi-frame, 100 millisecond, divided by the length of a slot gives the number of slots. Let c denote this value. Let the maximum transmission range of each vehicle be r. To simplify analysis, we utilize hard thresholding and assume symmetry to specify the vehicles which are able to receive transmissions from other vehicles. Without any other transmissions on air, each vehicle in a distance r of a transmitter can receive its packets. Vehicles which are in distance less than r from one another are called *neighbors*. Let us further assume that the vehicles are distributed uniformly at random on a horizontal line, such that there are q vehicles in a distance of r. With the above assumptions, the minimum number of necessary channels to let all vehicles reserve one is $2q-1$. This is the lower bound, because according to DCR, each vehicle can reserve a channel, only if that channel is not taken by its neighbors, or neighbors of any of its neighbors. Each vehicle has $2q-2$ neighbors, so at least $2q-1$ distinct channels are required. We show that with $2q-1$ channels, there is a channel reservation which allows all vehicles to own a channel, and therefore, $2q-1$ is a feasible minimum. As we

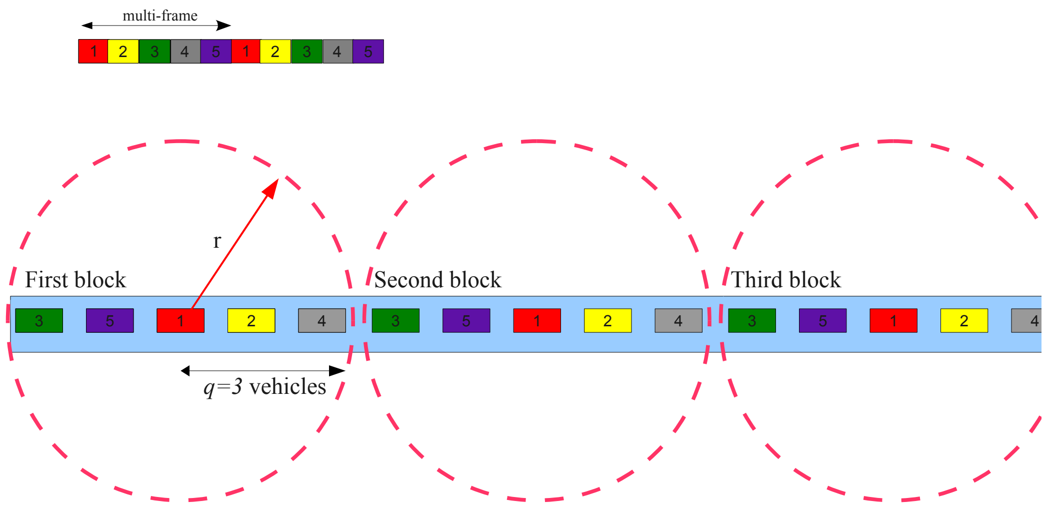


Figure 3.1: An illustration of the case where the number of slots is enough, and following the same order as the order in the first block allows all vehicles to choose a channel.

are considering vehicles in a lane of traffic, we can consider a natural ordering among them based on their position in the lane of traffic. Now consider the virtual block of the first $2q - 1$ vehicles and their corresponding channels. Let the order of these vehicles define the order among their channels. For example, if channel 3 is allocated to a vehicle which appears before a vehicle that has reserved channel 1, then channel 3 appears before channel 1 in this ordering. If the same order of channels repeats in the rest of the blocks, we have a feasible channel allocation according to the DCR protocol. Figure 3.1 shows an instance of this case for q=3.

On the other hand, if order is not preserved, some vehicles will be unable to reserve a channel when $c = 2q-1$. Figure 3.2 is an illustration of this situation where $q = 2$. The vehicle marked with a question mark is unable to choose any channels because the order specified by the channels occupied by the first three vehicles is not followed by the rest of the vehicles. We are interested to know the number of channels required to prevent such situations. In other words, we are interested in finding the minimum number of channels which guarantees a feasible channel allocation according to DCR, for a given density of vehicles (q cars in a distance of r). We show that with $c = 4q - 3$ this requirement is met. Let v denote a vehicle which has not yet reserved any channels. Vehicle v receives packets from $2q - 2$ of its neighbors. Therefore, $2q - 2$ channels are taken and cannot be used by v. Furthermore, v receives

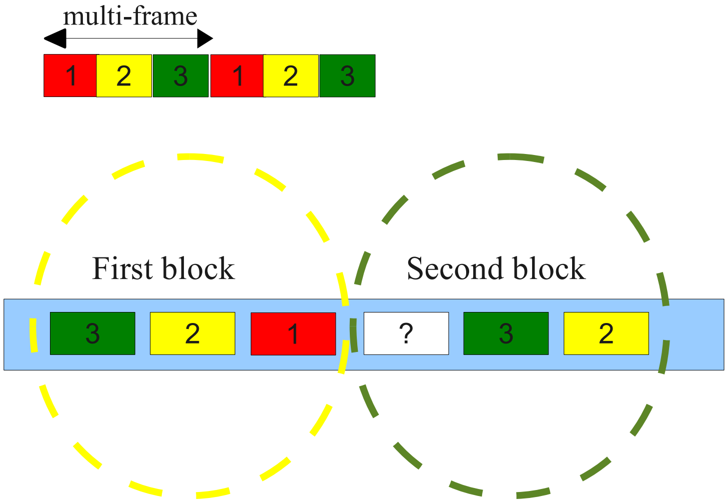
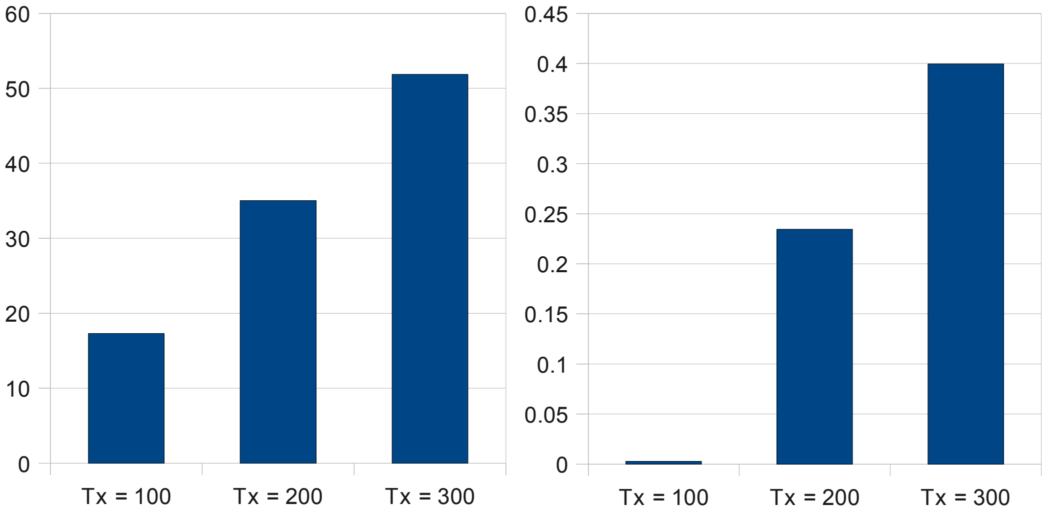


Figure 3.2: An illustration of the case where the number of slots is enough, but the current reservation prevents a vehicle from choosing any channels.

an availability bitmap from each neighbor and should choose a channel which is not marked as taken in the union of all received bitmaps. Let v_l denote the farthest neighbor from v on its left side, and let v_r be its farthest neighbor on its right. As the transmission range of each vehicle consists of a circle of radius r, centered at that vehicle, the availability bitmap of any other neighbor of v is covered by the union of v, v_l and v_r's availability bitmaps. Without loss of generality, consider a neighbor of v, denoted by v_n, positioned between v_l and v. All neighbors of v_n which appear on its right side are also neighbors of v. Therefore, their channel occupation is also marked in v's availability bitmap. On the other hand, all neighbors of v_n which are located on its left side are also v_l's neighbors. Thus, v_n's availability bitmap is covered by the union of v_l and v's availability bitmaps. The case where v_n is located between v and v_r is similar, and we do not repeat the reasoning again. It is, therefore, enough to consider the constraints imposed by v_l and v_r on v for its channel reservation. Vehicle v_l has at most $2q-3$ neighbors excluding v itself, but $q-2$ of them are also neighbors of v. Thus, the availability bitmap of v_l can cause at most $q-1$ other channels to be unusable for v. The same argument applies to v_r, so there are at most $4q-4$ channels taken by v's neighbors and their neighbors. Therefore, if $c \geq 4q-3$, every vehicle is guaranteed to be able to reserve a channel.



(a) (b)

Figure 3.3: (a) The average number of neighbors per vehicle in three different transmission ranges. (b) The average percentage of vehicles experiencing starvation in DCR for three different transmission ranges.

3.1 Starvation in DCR

In the previous section, we identified the necessary number of channels which guarantees a feasible channel reservation according to DCR. DCR does offer a plan for the cases where this requirement is not met. In other words, if the number of channels is not enough for the current density of vehicles, some vehicles cannot reserve a channel and remain silent. Lam and Kumar in [13] suggest leaving one channel for silent vehicles to announce their presence by transmitting a special packet in that channel. This scheme is used to estimate the number of vehicles in a two-way road, in order to allocate enough channels based on the density of cars on each side of the road. Nevertheless, in a one-way road, DCR does not accommodate the case where there are not enough channels. Therefore, DCR does not provide a fair allocation of bandwidth to the present vehicles, which is of utmost importance in most safety applications. Note that even when $c = 2q - 1$, an inconsistent channel reservation can cause some of the vehicles to remain silent and possibly face starvation.

Figure 3.3 shows the results of a preliminary experiment with 150 cars and $c = 64$ channels. The results shown are the average of 10 runs over a 30-

second-long experiment. The details of generating the traffic traces can be found in Chapter 5. We run the experiments for three transmission ranges, which results in three different q values. Figure 3.3(a) shows the average number of neighbors for different transmission ranges. Figure 3.3(b) reports on the average number of silent vehicles for their different transmission ranges. As can be seen, in the case of transmission range 100, $Tx = 100$, where the average number of neighbors is $q = 17$, the number of starving cars is almost zero, which is in accordance with our results on the necessary number of channels. For $Tx = 300$, almost 40% of the vehicles face starvation.

3.2 Fair DCR: fDCR

In this section we introduce our modified DCR scheme, *fDCR*, which aims at providing a fair allocation of channels even when the number of channels is not enough for a given density of vehicles. This scheme is later used to enable transmission power adjustment which consequently adapts the number of neighbors to the available number of channels.

The main difference between fDCR and DCR is that in fDCR each vehicle tries to find the channel which is likely to incur the minimum number of packet collisions in nearby distances and does not restrict channel contention to available channels only. This design goal is based on the new findings in a recent paper [1], which show that certain safety applications perform best when periodic beacons are received from nearby vehicles in a timely manner. fDCR achieves this goal by employing a weighting scheme and probablistical channel contention. In the following, we describe fDCR.

Similarly to DCR, each vehicle transmits its packets periodically in its reserved channel. The availability and collision bitmaps, described in Section 2.1 are piggybacked on each transmitted packet. The main difference between DCR and fDCR is the way a vehicle contends for a channel. Each vehicle, upon joining the network, listens to its neighbors and gathers information. For each time channel, a vehicle maintains a number of statistics based on its sensed and reported information. More specifically, it counts the number of times that channel is reported as taken (its corresponding bit is set in a received availability bitmap, or the vehicle itself has received a packet in that channel), the number of times it is reported as collisioned (its corresponding bit is set in a received collision bitmap, or the vehicle itself has sensed a packet collision during that time channel), and the number of times a channel is reported as available. After multiple multi-frames of information gathering (in our case three multi-frames), each channel is assigned a weight based on the above information:

$$w(i) = \begin{cases} \mathit{MAXVALUE} & \textit{if taken(i) = 0} \\ \mathit{empty}(i)/\mathit{taken}(i) & \textit{otherwise} \end{cases} \tag{3.1}$$

where $w(i)$ is the weight assigned to channel i, $\mathit{taken}(i)$ is the number of times channel i is reported as taken, and $\mathit{empty}(i)$ is the number of times channel i is reported as empty. $\mathit{MAXVALUE}$ is a fixed large number that is larger than c (note that $c-1$ is the maximum value $\mathit{empty}(i)/\mathit{taken}(i)$ can take for any i under all circumstances).

After normalizing all channel weights, the vehicle chooses a channel at random, where the probability of a channel being chosen is proportional to its weight. fDCR does not have a probing phase, because when the number of channels is less than required, some vehicles are never able to own a channel due to receiving reports of collision and their probing would never succeed. Therefore, in fDCR, once a channel is chosen, the vehicle starts broadcasting in that channel for a fixed number of multi-frames (in our case, three). If it does not receive a report of collision in its owned channel, it continues broadcasting in that same channel until it receives a report of collision. Once an owner of a channel receives three consecutive reports of collision on its owned channel, it will repeat the channel contention procedure as explained above with a slight difference. If channel j is owned by this vehicle, the following weighting scheme is applied to it:

$$w(j) = \begin{cases} \mathit{MAXVALUE} & \textit{if collision(j) = 0} \\ \mathit{taken}(j)/\mathit{collision}(j) & \textit{otherwise} \end{cases} \tag{3.2}$$

where $\mathit{collision}(j)$ is the number of times a collision was sensed in channel j by neighbors.

With the above procedure, more heavily weighted channels have a higher chance of being chosen. The weighting scheme is designed such that if a channel is chosen by two or more vehicles not at enough spatial distance from each other, the damage caused by the potential packet collisions is minimized.

Also, note that with this scheme channels already occupied by immediate neighbors of a vehicle are less likely to be chosen, because many neighbors of this vehicle also sense them as taken and the denominator value in Equation 3.1 is large, causing the weight to be a small value and consequently that channel to be chosen by a smaller probability. Furthermore, with the above scheme, potential collisions caused by choosing an already taken channel, are more likely to happen in a larger distance from the transmitter. This is again due to the contiguous nature of neighborhood in wireless communications: An owned channel by a vehicle closer to a choosing vehicle has more common neighbors with that vehicle than a taken channel owned by a vehicle at a greater distance.

3.3 Transmission Power Control

fDCR solves the starvation problem, in which some vehicles cannot transmit for a long duration of time, in DCR and allows the vehicles to have a fair allocation of bandwidth. However, when the number of channels is not enough to accommodate all vehicles, some channels will be utilized by vehicles which are not at a large enough spatial distance from each other, which will inevitably cause packet collisions at the intersection of the transmission ranges of such vehicles. In order to avoid causing collisions and overwhelming the wireless channel, the transmission power level can be adjusted, to effectively decrease the average number of neighbors. Note that the number of channels cannot be changed, as this value is bound to the fixed frequency of safety messages (usually 10 per second) and their sizes (200-500 bytes). In this section we propose a low overhead power control scheme for fDCR which utilizes the availability and collision bitmaps received over a period of time. Our proposed scheme, fDCRp, is completely distributed and all decisions are made locally.

The goal of our transmission power control scheme is to adjust the transmission power, such that the number of neighbors matches the minimum number of necessary channels, which allows for vehicles to contend for available channels only. As we previously proved, the minimum number of necessary channels is $2q-1$. Each vehicle monitors all channels and counts its neighbors. If this value is larger than $2q-1$, it decreases its transmission power by a predefined delta value ΔP. A vehicle v counts the number of its neighbors to be the sum of the number of availability bitmaps which marked v's channel as taken, plus the number of collision bitmaps which marked v's channel as collisioned, plus, pessimistically, the number of channels in which v sensed a collision. The power management function is triggered every four multi-frames and the average of the above value in each multi-frame is used as the number of neighbors upon which the power adjustment is performed.

Our fDCRp has a procedure for increasing the transmission power which is similar to decreasing the transmission power. Once the number of neighbors is less than what guarantees a possible channel allocation with regard to the number of channels, $c/4 + 3$, the transmission power is increased by a delta value ΔP (to aim at increasing the number of neighbors). The number of neighbors is calculated as described above.

Each time an adjustment is made to the transmission power, an *adjust counter* is set to three. This counter is decreased each time the power control procedure is triggered. Nevertheless, further adjustments are performed only when the counter reaches zero or below that. The adjust counter is used to ensure that the effect of decreasing or increasing the power is sensed in the network before any further changes. More specifically, in fDCR, a vehicle changes the status of a channel from taken to available only after it has not received transmissions on that channel for three consecutive multi-frames. Therefore, there is a delay associated with updating the status of a channel and reporting it later, which should be considered when adjusting power. Algorithm 1 presents our power control procedure, fDCRp.

```
Input: power_counter, #slots, adjust_counter
power_counter++;
if power_counter == $4 \times$ num_slots then
    adjust_counter - -;
    if #neighbors $\geq$ #slots/2 and adjust_counter $\leq$ 0 then
        decreasePower();
        adjust_counter = 3;
    else if #neighbors $\leq$ #slots/4 and adjust_counter $\leq$ 0 then
        increasePower();
        adjust_counter = 3;
    end
end
```

Algorithm 1: The power control procedure in fDCRp.

3.3.1 Uniform Transmission Power Control

In the transmission power control scheme described in Section 3.3, each vehicle increases or decreases its power level independent of others in the network, solely based on an estimate of the number of its neighbors. This procedure may cause asymmetry in transmission ranges of nearby vehicles, because they may have different perceptions of the environment. This may jeopardize the feedback-based nature of DCR and fDCR, which are both based on detecting collisions from neighbors' reports. In this section we propose an addition to fDCRp, fDCRpU, to achieve uniform power levels.

Before describing fDCRpU, we first explain the complications caused by non-uniform power levels. In DCR, as well as fDCR, when a vehicle receives the availability and collision bitmaps of its neighbors, it assumes that the corresponding bit to its channel in those bitmaps concerns its own transmissions. This is not the case when the transmission ranges of nearby vehicles are not similar which may result in several undesirable consequences.

Let vehicle v_s have a short transmission range which does not reach vehicle v_b. On the other hand, assume v_b has a long transmission range and v_s is located in v_b's transmission radius. The following is a list of possible results of uneven transmission ranges:

- False Channel Give-up: v_s may give up its own channel due to receiving a collision report from v_b concerning its time channel, while this report in reality concerns another transmission, because v_b cannot receive v_s's transmissions.
- False Power Decrease: v_s may further decrease its transmission power level, because it counts v_b as one of its neighbors, while v_b has another neighbor on the other side which uses the same time channel as v_s.
- Repeating Collisions: v_s may sense collisions in v_b's channel, but its collision bitmap does not reach v_b.
- False Power Increase: v_b may further increase its transmission power level, because it does not receive v_s's transmissions and does not have a good estimate of the number of its neighbors.

Clearly, the above cases happen when there are multiple vehicles with different power levels, but for simplicity we have described these cases using only two vehicles.

fDCRpU strives to achieve uniform transmission power by utilizing a feedback propagation scheme. Each time a vehicle changes its power level, it announces this change by piggybacking a power adjustment status on the periodic messages that it transmits. The power adjustment flag is a three-bit flag, thus adding very little overhead. It takes one the following values: "nochange", "decreased", "neighbor_decreased", "increased", and "neighbor_increased". Vehicles that have decreased or increased their power level as a result of the number of neighbors test presented previously, announce this change by setting their adjustment flag to "decreased" or "increased" according to the change they have made. Once a vehicle receives a packet from a neighbor with an adjustment flag value of "decreased" or "increased", it adjusts its power accordingly (by decreasing or increasing it by ΔP) and sets its adjustment flag to "neighbor_decreased" or "neighbor_increased" respectively. The change in the adjustment flag is for limiting the propagation of power adjustment to within a reasonable radius of the vehicle that changed its power level. A vehicle receiving an adjustment flag with values "neighbor_decreased" or "neighbor_increased" also adjusts its power accordingly but sets its own adjustment flag to "nochange" and by this, terminates the propagation. Algorithm 2 presents the details of this scheme.

```
Input: power_counter, #slots, adjust_counter, #neighbors
power_counter++;
if $power\_counter == 4 \times \#slots$ then
    adjust_counter - -;
    if $\#neighbors \geq \#slots/2$ and $adjust\_counter \leq 0$ then
        decreasePower();
        adjust_flag = DECREASED;
        adjust_counter = 3;
    else if $\#decreased>0$ and $adjust\_counter\neq 2$ then
        decreasePower();
        adjust_flag = NEIGHBOR_DECREASED;
        adjust_counter = 2;
    else if $\#neigh\_decreased>0$ and $adjust\_counter\leq 0$ then
        decreasePower();
        adjust_flag = NOCHANGE;
        adjust_counter = 2;
    else if $\#neighbors \leq \#slots/4$ then
        increasePower();
        adjust_flag = INCREASED;
        adjust_counter = 3;
    else if $\#increased>0$ and $adjust\_counter\neq 2$ then
        increasePower();
        adjust_flag = NEIGHBOR_INCREASED;
        adjust_counter = 2;
    else if $\#neigh\_increased>0$ and $adjust\_counter\leq 0$ then
        decreasePower();
        adjust_flag = NOCHANGE;
        adjust_counter = 2;
    else
        adjust_flag = NOCHANGE;
    end
end
```

Algorithm 2: The power control procedure in fDCRpU.

CHAPTER 4

CROSS-THROUGH TRAFFIC

Providing cross-traffic assistance at intersections is an important feature of safety systems in VANETs. This application is mainly motivated by the high number of vehicle crashes that occur at crossings in urban settings. It is therefore of utmost importance to ensure vehicles close to an intersection receive complete information from other vehicles approaching the intersection in a timely manner. However, reception rate and quality of wireless communication in the proximity of intersections is different from communication along a road, mainly due to buildings which cause some vehicles to be in non-line-of-sight (NLOS) with regard to one another. Although there have been doubts on the reliability of NLOS reception due to the high operational frequency of 5.9GHz which is the standard often used in VANET, recent field studies in urban settings report acceptable reception qualities [14]. For example, in [14] it is reported that if two vehicles approach an intersection from crossing streets at the same time, 50% reception rate is reached at 50 meters to the intersection center. At 30 meter, rates are as high as 80%. However, the lower reception power in NLOS can increase the probability of hidden terminals [1] in smaller distances compared to line-of-sight (LOS) communications.

Figure 4.1 presents received power values in NLOS and LOS communication. We have used a simulation which approximates received power levels at intersections [15, 8]. As can be seen from the figure, received power level drops significantly faster in NLOS compared to LOS when the two wireless devices are at equal distance in both cases. This can cause more packet collisions to happen in the proximity of intersections in IEEE 802.11p.

Because broadcast in 802.11p is performed without handshake schemes

---

[1] Hidden terminals occur when two wireless devices which are not in each other's carrier sense (CS) distance transmit at the same time and there is a receiver within the transmission range of both of them.

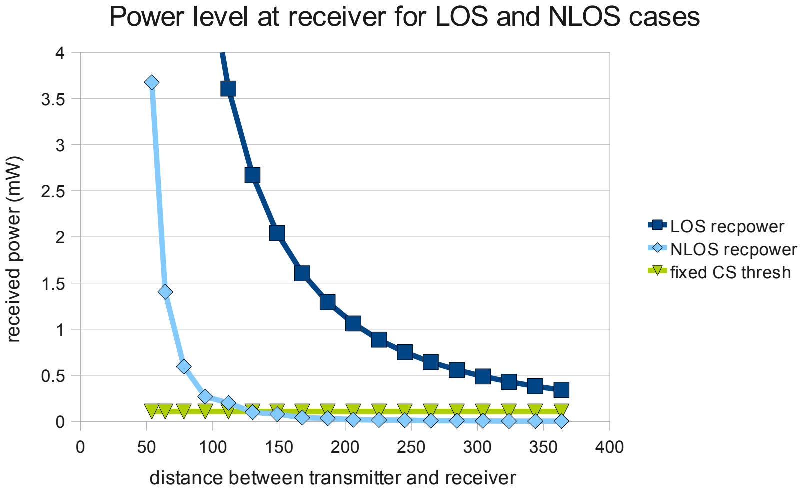


Figure 4.1: Received power values in NLOS and LOS communication.

such as RTS/CTS, it is vulnerable to the hidden terminal problem. Hidden terminals due to NLOS happen for vehicles closer to intersections. This is because the transmission range is much shorter in NLOS, as can be seen also from Figure 4.1, compared to LOS transmissions. A vehicle close to an intersection is within NLOS transmission range of another cross-through vehicle close to that intersection. However, vehicles slightly farther from the intersection are not in the CS range of this vehicle, and as a result vehicles close enough to intersections can experience packet collisions.

We expect to observe a larger number of packet collisions at intersections even if DCR is used. Let us assume vehicles move with constant, equal speed and there are enough channels to accommodate all vehicles on a road. In this case, once DCR has passed the start-up phase and all vehicles have chosen their channels, no packet collisions happen when there is no NLOS communication. However, vehicles on crossing roads may have chosen the same channel (this can happen if these vehicles are in two-hop distance from each other). There will be packet collisions when two such vehicles approach the intersection and one of them is able to have NLOS communications with a neighbor of the other vehicle. Figure 4.2 illustrates an instance of this scenario.

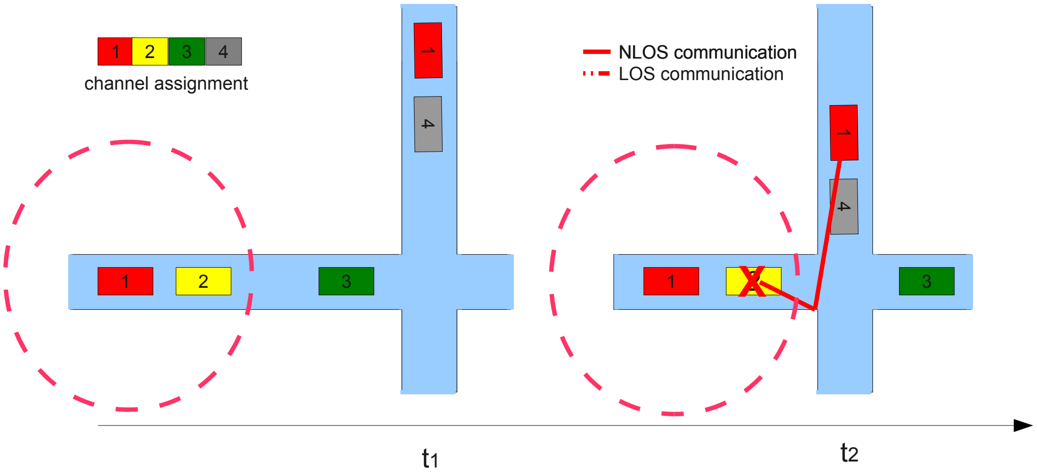


Figure 4.2: An instance of packet collision caused at intersection with DCR.

CHAPTER 5

EXPERIMENTAL RESULTS

We have implemented our proposed scheme in the NS-2 simulator which is a discrete event simulator targeted at networking research. Our implementation of fDCR builds on the original implementation of DCR [6] which the authors have generously provided us with. We evaluate the performance of our scheme against the IEEE 802.11p protocol under standardization. It should be noted that the DCR protocol has been implemented with respect to the way the Mac802_11 module in NS-2 simulates the wireless medium and collisions to provide a fair comparison of the two protocols. We run simulations under realistic VANET scenarios with vehicle mobility patterns generated using the VanetMobiSim engine [16] as described in the following.

Trace Generation

We use VanetMobiSim [16] to generate our traces. We use two urban layouts. The first is a single road, and the second consists of two roads crossing a third one as shown in Figure 5.1. In the crossing layout(b), parallel roads have a distance of 400 meters from each other. To generate traffic, we specify traffic flows using the Intelligent Driving Model with Lane Changing as described in [17]. The VanetMobiSim engine generates two-way traffic. In order to force generating one-way traffic, we specified the beginning of each road as a possible start point and the end of it as an end point. This causes all cars to start at the same point; however, they start moving at different times and with different speeds, so at some point they are not overlapping any more. We performed data cleaning on the generated traces to remove the time period where cars are overlapping. Each vehicle is five meters long and maintains a safe headway time of 1.5 s from the vehicle in front of it. In order to generate traces with different levels of congestion, we have varied the number of vehicles as well as their speed. Table 5.1 lists the parameters

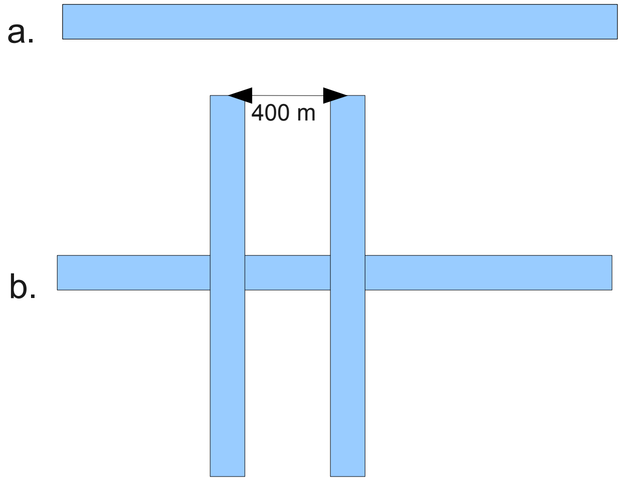


Figure 5.1: Layouts used in trace generation: (a) a single road of length 3 km; (b) two roads crossing a third one, used for experimenting cross-through traffic.

used in each trace. We generate ten traces from each scenario using different seeds, and each of our simulations is run with a different one of these traces. It should be noted that the number of vehicles in each trace may be slightly smaller than the initial number reported in Table 5.1 due to the data cleaning we performed to remove overlapping vehicles.

Algorithms Under Comparison

We evaluate the following proposed algorithms:

- fDCR : This is the MAC protocol based on DCR, as described in Section 3.2. Its goal is to provide a fair channel reservation scheme where all vehicles are able to reserve a time channel and transmit periodic beacons during that time slot. It uses the availability and collision bitmaps which were introduced in DCR to assign weights to channels. Channels are chosen with probabilities proportional to their weights.
- fDCRp: This is the transmission power control scheme that is added to fDCR, as described in Section 3.3, to avoid overwhelming the wireless medium in high-density scenarios. It is a completely distributed power control protocol which adjusts the transmission power based on an

Table 5.1: Parameters used in generation of four different trace scenarios.

Trace	#cars	min speed (m/s)	max speed (m/s)	layout
1-0road150	150	8	11	a
1-0road350	350	5	8	a
1-2road200	200	5	8	b
1-2road400	400	5	8	b

estimate of the number of neighbors each vehicle has and its relation to the number of channels. It does not incur extra overhead compared to fDCRp.

- fDCRpU: This is the power control protocol as described in Section 3.3.1. It uses a feedback-based method to maintain the symmetry in transmission ranges of nearby vehicles as a principle required by DCR. The extra overhead incurred by this protocol is a three-bit flag indicating the type of change each vehicle has made to its transmission power.

Propagation Model

To have a more realistic simulation, we use CORNER [8] as our propagation model. We have adapted the CORNER implementation to be used in NS-2. CORNER provides a more realistic propagation model with a still low computational cost. In this model, sender and receiver are classified as in line-of-sight (LOS) when they are on the same road and there are no obstacles between them, and as non-line-of-sight (NLOS) when they are traveling in perpendicular roads and there are obstacles (such as buildings) between them. When the sender and receiver are classified as LOS, CORNER uses the standard TwoRay Ground model to simulate radio prediction.

Each simulation run is repeated for each of the 10 generated traces with a different random seed. The total length of each simulation run is 45 seconds for single road layouts and 55 seconds for the crossing layout. We specify a warmup period of 15 seconds before we gather network statistics. The results shown are averaged over 10 runs. The NS-2 parameters used are listed in Table 5.2. It should be noted that the $Pt\_$ parameter corresponds to initial transmission powers per vehicle. While this value remains the same throughout the experiments in 802.11p, fDCRp and fDCRpU adjust this

Table 5.2: Medium access, physical layer, and periodic broadcast configuration parameters used in the NS-2 simulations.

Layer	Parameter	Value
PhyWirelessPhy	CSThresh_	1.07577e-12
PhyWirelessPhy	Pt_	0.0275398
PhyWirelessPhy	freq_	5.9e9
PhyWirelessPhy	L_	1.0
PhyWirelessPhy	RXThresh_	5.01e-12
PhyWirelessPhy	CPThresh_	10.0
MAC802_11	CW_Min_	15
MAC802_11	CW_Max_	1023
MAC802_11	SlotTime_	0.000013 s
MAC802_11	SIFS_	0.000032 s
MAC802_11	ShortRetryLimit_	7
MAC802_11	LongRetryLimit_	4
MAC802_11	PreambleLength_	60 bits
MAC802_11	PLCPHeaderLength_	60 bits
MAC802_11	PLCPDataRate_	3.0e6 bps
MAC802_11	RTSThreshold_	2346 bits
MAC802_11	basicRate_	3.0e6 bps
MAC802_11	dataRate_	3.0e6 bps
MACfDCR	bandwidth_	3.0e6 bps
MACfDCR	ChannelTime_	0.0015625 s
MACfDCR	NumChannels_	64
PBC	packetSize	500 bytes
PBC	broadcast freq	10 per sec

value according to congestion as described previously in Section 3.3.

Results

The goal of these simulations is to compare the packet reception probability of the different algorithms under comparison. The simulation results plotted in Figure 5.2 show the probability of receiving a packet based on the distance between transmitter and potential receiver for the 1-0road150 scenario. This metric is measured at the receiver side by dividing the number of received packets by the number of packets which should have been transmitted within a distance r from the receiver that potentially could be received, but may be lost due to collisions.

fDCR and 802.11p perform similarly for this scenario. Note that DCR faces up to 40% starvation in this scenario, which is the lowest density we have used in the experiments (see Section 3.1 and Figure 3.3). Both power control schemes result in power reduction, with fDCRpU maintaining higher probability of reception for closer distances. Figure 5.3 presents the reception probability for the 1-0road350 scenario. The reception probability of 802.11p decreases compared to the lower density scenario of 1-0road150. However,

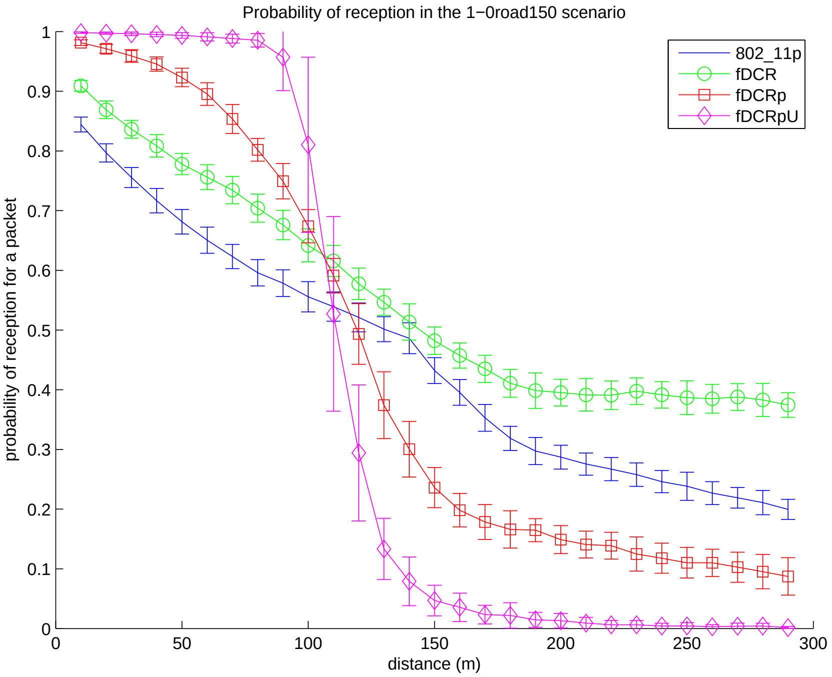


Figure 5.2: Reception probability for 1-0road150.

fDCR is able to better maintain the reception probability. In distances below 100 meters we see a difference of 20% in the percentage of received packets by comparing 802.11p and fDCR. This confirms previous findings that the performance of 802.11p degrades under high density scenarios. Again the power control schemes result in power reduction, and maintain very good probability of reception for smaller distances. Note that clearly the power levels have fallen less than the case for 1-0road150. We observe higher than 80% probabilities for distances less than 60 meters for this scenario, while for the 1-0road150 scenario this value is around 100 meters. This indicates that fDCRp and fDCRpU adapt very well to the density of vehicles. Figures 5.4 and 5.5 show the reception probabilities for the cross-through traffic scenarios. We observe the same trend as in the previous cases. Again in the high-density scenario fDCR performs better than 802.11p and in both cases, transmission power is adjusted to meet the requirements of the reservation scheme.

Figure 5.6 presents a comparison between the two transmission power control protocols, fDCRp and fDCRpU. This measurement is done for the 1-0road150 scenario. Figure 5.6 (top) shows each vehicle's power level, plotted against its position on the road. Figure 5.6 (bottom) shows the number of

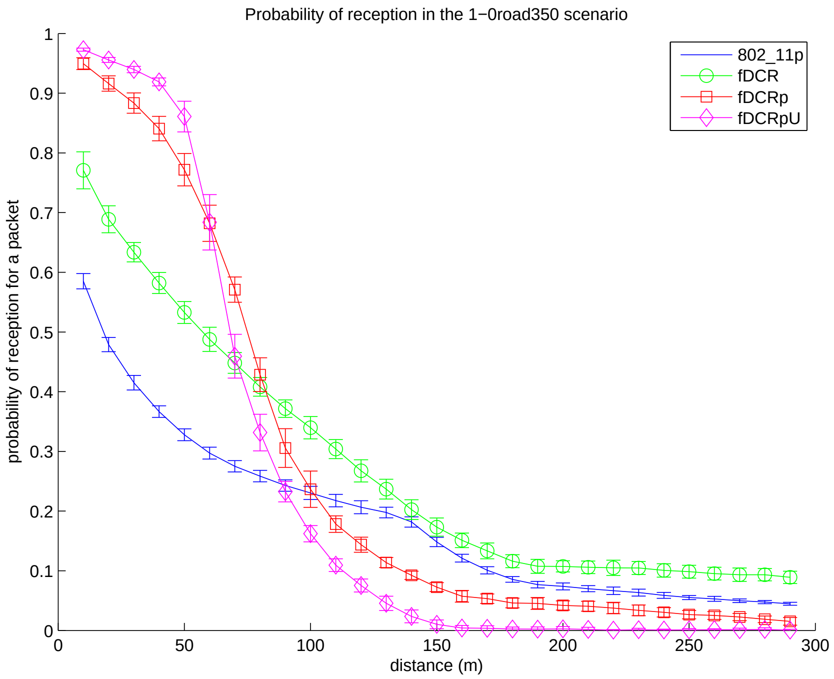


Figure 5.3: Reception probability for 1-0road350.

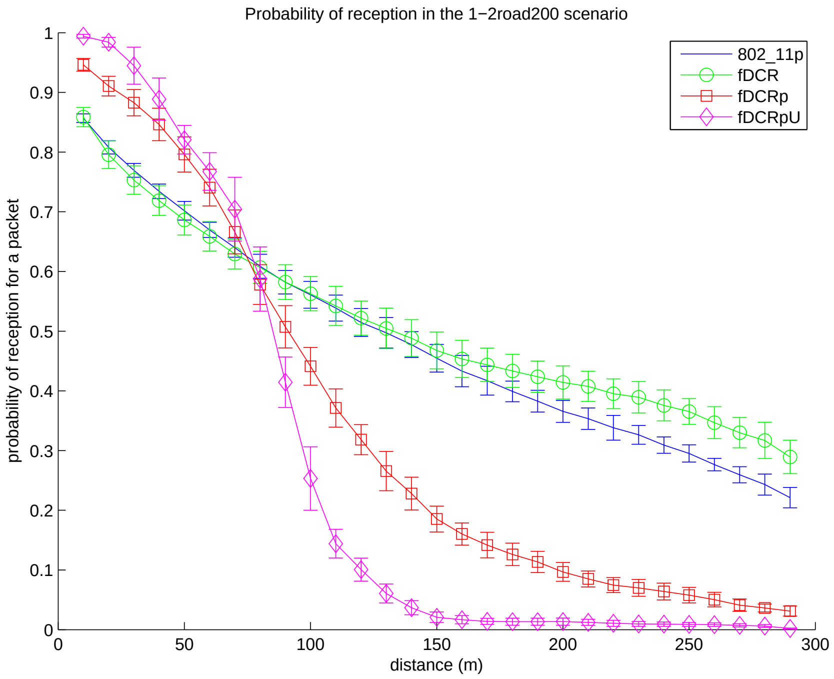


Figure 5.4: Reception probability for 1-2road200.

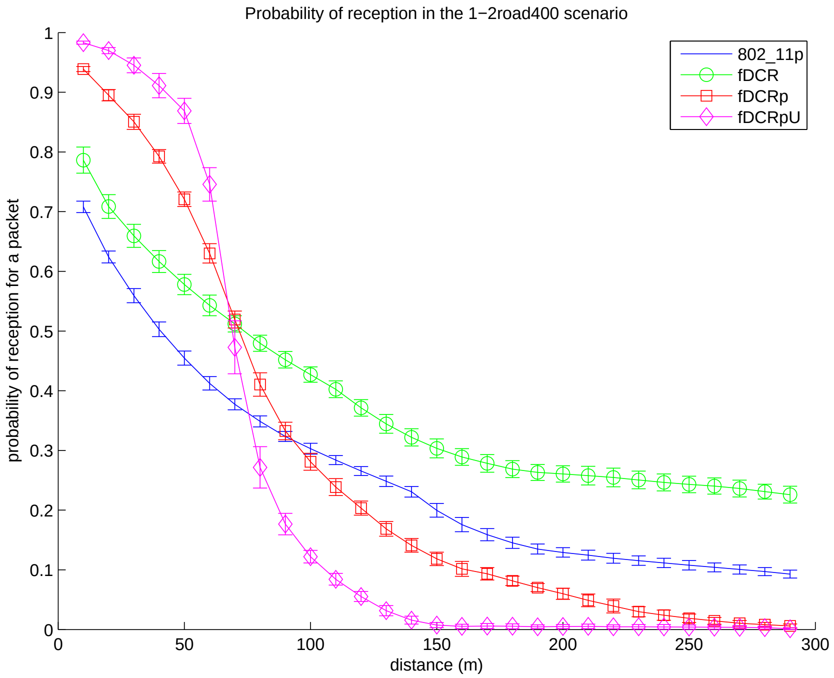


Figure 5.5: Reception probability for 1-2road400.

neighbors each vehicle has in a radius of 300 meters, which corresponds to the maximum transmission power level. As can be seen, the power levels in fDCRp correspond to the differences in the number of neighbors each vehicle has and form a similar pattern. However, fDCRpU achieves more uniform power levels.

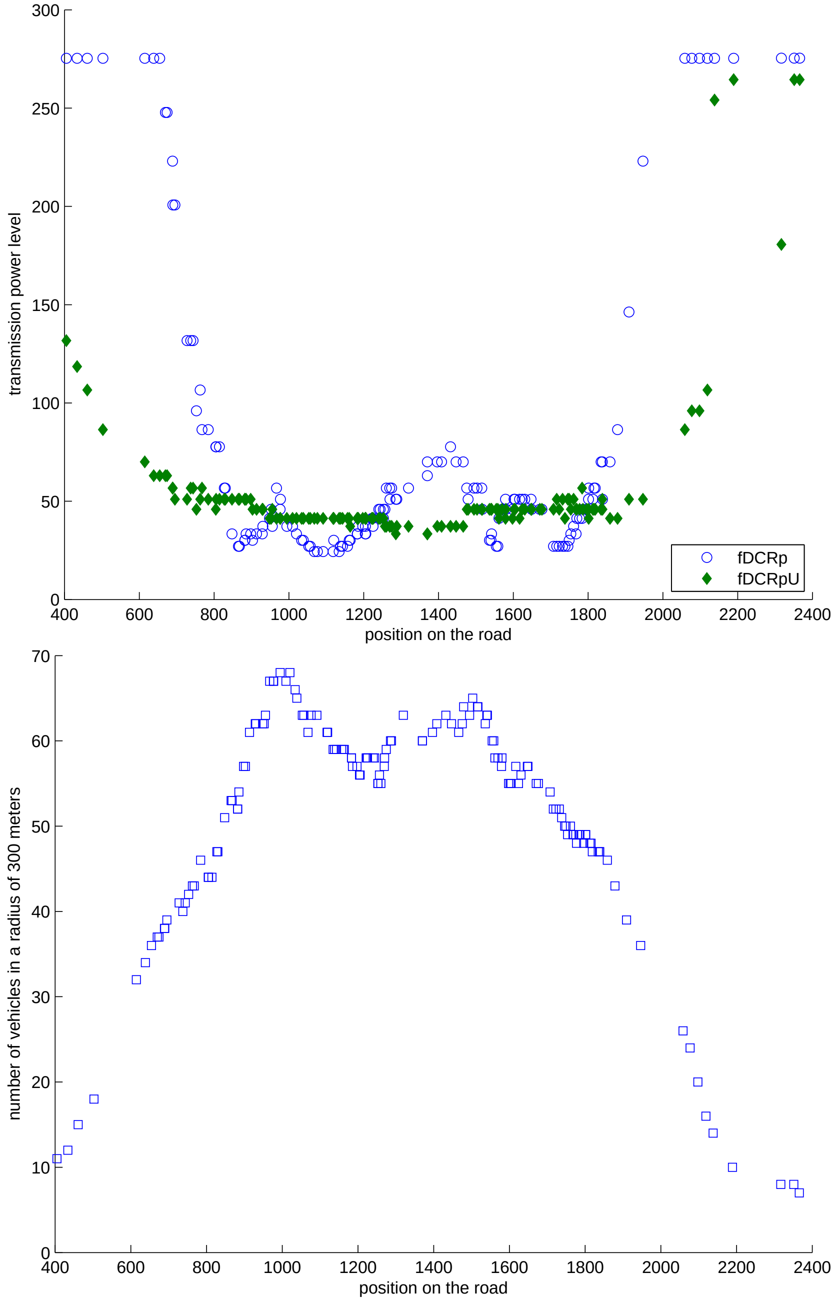


Figure 5.6: Comparison of power levels in fDCRp and fDCRpU in 1-0road150: (top) transmission power based on the position of the car on the road; (bottom) number of neighbors in a radius of 300 meters based on the position of the car on the road.

CHAPTER 6

CONCLUSION

In this thesis we investigate the performance of two Medium Access Control protocols, DCR and 802.11p. DCR has shown significant improvements over 802.11p by utilizing the group behavior of vehicles in vehicular networks and moving to a reservation-based protocol. However, DCR does not accommodate the case where the number of channels is not sufficient for a given density of vehicles. As a result, vehicles that are unable to reserve a channel, remain silent and may face starvation. Based on this observation, we introduce Fair Dynamic Channel Reservation, fDCR, which leverages on the feedback information received from neighboring vehicles to assign weights to channels and choose a channel probabilistically proportional to its weight. fDCR is a fair reservation scheme, because all vehicles have equal chances in choosing a time channel, and no advantage is given to vehicles which have chosen a channel earlier. In high-density scenarios, a time channel may be reserved by several vehicles, which are not at great enough spatial distance from each others to avoid packet collisions. However, the weighting scheme in fDCR is designed so that these collisions are more likely to occur at distances farther away from the transmitter. This is in accordance with the communication requirements which were recently recognized for safety applications.

In order to avoid flooding the network under high-density scenarios, we propose a transmission power control scheme, fDCRp. fDCRp is based on our analysis of the required number of channels given the number of neighbors and incurs no extra overhead compared to DCR and fDCR. It is a completely distributed algorithm where each vehicle decides to increase or decrease its power based on an estimate of the number of neighbors it has. fDCRpU slightly differs from fDCRp by utilizing a feedback-based scheme to ensure uniform power levels, and consequently symmetric transmission ranges in nearby vehicles. Its overhead consists only of a three bit adjustment flag which propagates the change a vehicle has made in its power level.

We perform extensive experiments and compare our proposed protocols with 802.11p. The results show significant improvements in terms of reception rate for fDCRp under high density, especially in nearby distances which are of great importance. The proposed transmission power control schemes show great performance, adapting the transmission range to the density such that more important packets (those transmitted from a nearby vehicle) have an excellent probability of being received.

REFERENCES

[1] J. J. Haas and Y.-C. Hu, "Communication requirements for crash avoidance," in *Proceedings of the Seventh ACM International Workshop on VehiculAr InterNETworking*, ser. VANET '10, 2010, pp. 1–10.

[2] X. Ma and X. Chen, "Performance analysis of IEEE 802.11 broadcast scheme in ad hoc wireless LANs," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 6, pp. 3757–3768, Nov. 2008.

[3] M. Torrent-Moreno, D. Jiang, and H. Hartenstein, "Broadcast reception rates and effects of priority access in 802.11-based vehicular ad-hoc networks," in *Proceedings of the 1st ACM International Workshop on Vehicular ad hoc Networks*, ser. VANET '04, 2004, pp. 10–18.

[4] M. M. Artimy, W. Robertson, and W. J. Phillips, "Assignment of dynamic transmission range based on estimation of vehicle density," in *Proceedings of the 2nd ACM International Workshop on Vehicular ad hoc Networks*, ser. VANET '05, 2005, pp. 40–48.

[5] J. Mittag, F. Schmidt-Eisenlohr, M. Killat, J. Härri, and H. Hartenstein, "Analysis and design of effective and low-overhead transmission power control for VANETs," in *Proceedings of the Fifth ACM International Workshop on VehiculAr Inter-NETworking*, ser. VANET '08, 2008, pp. 39–48.

[6] R. K. Lam and P. R. Kumar, "Dynamic channel reservation to enhance channel access by exploiting structure of vehicular networks," in *IEEE 71st Vehicular Technology Conference (VTC 2010-Spring)*, May 2010, pp. 1–5.

[7] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta, "ADHOC MAC: New MAC architecture for ad hoc networks providing efficient and reliable point-to-point and broadcast services," *Wireless Networks*, vol. 10, pp. 359–366, Jul. 2004.

[8] E. Giordano, R. Frank, G. Pau, and M. Gerla, "Corner: A step towards realistic simulations for VANET," in *Proceedings of the Seventh ACM International Workshop on VehiculAr InterNETworking*, ser. VANET '10, 2010, pp. 41–50.

[9] N. Wisitpongphan, O. Tonguz, J. Parikh, P. Mudalige, F. Bai, and V. Sadekar, “Broadcast storm mitigation techniques in vehicular ad hoc networks,” *IEEE Wireless Communications*, vol. 14, no. 6, pp. 84–94, Dec. 2007.

[10] M. Torrent-Moreno, P. Santi, and H. Hartenstein, “Fair sharing of bandwidth in vanets,” in *Proceedings of the 2nd ACM International Workshop on Vehicular ad hoc Networks*, ser. VANET ’05, 2005, pp. 49–58.

[11] M. Torrent-Moreno, P. Santi, and H. Hartenstein, “Distributed fair transmit power adjustment for vehicular ad hoc networks,” in *3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks (SECON ’06)*, vol. 2, Sep. 2006, pp. 479–488.

[12] X. Guan, R. Sengupta, H. Krishnan, and F. Bai, “A feedback-based power control algorithm design for VANET,” in *Mobile Networking for Vehicular Environments*, May 2007, pp. 67–72.

[13] R. K. Lam and P. R. Kumar, “Dynamic channel partition and reservation for structured channel access in vehicular networks,” in *Proceedings of the Seventh ACM International Workshop on VehiculAr InterNETworking*, ser. VANET ’10, 2010, pp. 83–84.

[14] T. Mangel, M. Michl, O. Klemp, and H. Hartenstein, “Real-world measurements of non-line-of-sight reception quality for 5.9GHz IEEE 802.11p at intersections,” in *Communication Technologies for Vehicles*, 2011, vol. 6596, pp. 189–202.

[15] Q. Sun, S. Tan, and K. C. Teh, “Analytical formulae for path loss prediction in urban street grid microcellular environments,” vol. 54, no. 4, pp. 1251–1258, Jul. 2005.

[16] J. Härri, F. Filali, C. Bonnet, and M. Fiore, “VanetMobiSim: Generating realistic mobility patterns for VANETs,” in *Proceedings of the 3rd International Workshop on Vehicular ad hoc Networks*, ser. VANET ’06, 2006, pp. 96–97.

[17] J. Härri, F. Filali, and C. Bonnet, “Mobility models for vehicular ad hoc networks: A survey and taxonomy,” Institut Eurecom, Sophia-Antipolis, France, Tech. Rep. RR-6-168, 2006.