Broadcast Reception Rates and Effects of Priority Access in 802.11-Based Vehicular Ad-Hoc Networks

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ABSTRACT

One key usage of VANET is to support vehicle safety applications. This use case is characterized by the prominence of broadcasts in scaled settings. In this context, we try to answer the following questions: *i)* what is the probability of reception of a broadcast message by another car depending on its distance to the sender, *ii)* how to give priority access and an improved reception rate for important warnings, e.g., sent out in an emergency situation , and *iii)* how are the above two results affected by signal strength fluctuations caused by radio channel fading? We quantify via simulation the probability of reception for the two-ray-ground propagation model as well as for the Nakagami distribution in saturated environments. By making use of some IEEE 802.11e EDCA mechanisms for priority access, we do not only quantify how channel access times can be reduced but also demonstrate how improved reception rates can be achieved. Our results show that the mechanisms for priority access are successful under the two-way-ground model. However, with a non-deterministic radio propagation model like Nakagami's distribution the benefit is still obvious but the general level of probability of reception is much smaller compared to two-ray-ground model. The results indicate that – particularly for safety-critical and sensor network type of applications – the proper design of repetition or multi-hop retransmission strategies represents an important aspect of future work for robustness and network stability of vehicular ad hoc networks.

Categories and Subject Descriptors

C.2.1 [**Network Arquitecture and Design**]: Wireless communication; C.4 [**Performance of Systems**]: Performance attributes

General Terms

Performance, design

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Keywords

IEEE 802.11, broadcast reception rates, priority access, non-deterministic radio propagation model

1. INTRODUCTION

Currently, the 'range of awareness' of a driver in a vehicle is limited to what he/she can directly see with his/her eyes. Clearly, an increased range of awareness beyond line-of-sight could significantly improve safety and comfort of all passengers in a vehicle: information on emergency actions like emergency braking or hazards on the road can provide measures for active safety when received early enough. Information on traffic condition, in particular traffic jams, can help to save time on the road when accurate information is timely received. In the field of vehicle-to-vehicle communications one assumes that vehicles will be equipped with radio transceivers in order to directly exchange information within some communication range of, e.g., several hundreds of meters. Information can be relayed in order to allow larger communication ranges via multi-hop communication. Vehicle-to-vehicle communications and vehicular ad hoc networks are recently addressed, for example, within the DSRC (WAVE) working group [1] and in national collaborations like the German FleetNet and NOW projects [2, 3] or the Japanese Internet-ITS project [4].

A vehicular ad hoc networks (VANET) differs from usual ad hoc networks by its vehicular environment, distributions, movement and applications. The technical considerations in a VANET's design should be influenced accordingly. Given the (likely) emphasis on supporting vehicle safety applications[1], it is expected that broadcast operations for informing the immediate neighborhood will constitute a key part of a VANET's usage. This is because vehicle safety communication is essentially about informing neighboring vehicles of one's own change of state (velocity, lane changing intention, etc.). For this purpose, broadcasts are the natural approach.

This paper attempts to study how broadcast performance scales in vehicular environments. Furthermore, we address the question of how well a priority mechanism is able to work in these environments. The technology being examined is IEEE 802.11 [5] because the aforementioned DSRC technology is going to be based on an slightly adjusted IEEE 802.11a PHY and MAC. Additionally, there are also interests elsewhere, such as in Europe, in pushing for the

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[1] The U.S. Federal Communications Commission (FCC) allocated a block of spectrum in the 5.850 to 5.925 GHz band primarily to enhance safety of the transportation system.

same approach. For our studies we have implemented a ns-2 [6] module for an 802.11a [7] variant at 5.9GHz with 10MHz channels, following current DSRC proposals [1]. While vehicular ad hoc networks will suffer from small penetration rates within the first years of existence, we expect that when these networks will be successfully deployed they will operate most of the time under saturation conditions due to restrictions in bandwidth. A broadcast message will not be received by all neighbors within a circular transmission range of a sender (as given by the two-ray-ground model or any unit disc graph model), but will suffer collisions either due to two or more direct neighbors accessing the channel at the same time or due to the well-known hidden terminal problem. We provide quantitative results of the probabilities of reception.

Inspired by the Enhanced Distributed Channel Access (EDCA) of IEEE 802.11e [8], we outline a priority access mechanism and analyze its performance with respect to channel access times and to probability of reception. When using the two-ray-ground model as radio propagation model, the priority access mechanism leads to smaller access times *and* a higher reception probability for messages of the prioritized sender. We analyze in detail why the method can achieve improved reception probabilities.

Finally, we investigate the impact of a non-deterministic radio propagation model on the probability of reception and on the success of the priority access mechanism. In [9] and [10] it was shown for other metrics than the one we address in this paper that results can heavily depend on whether a radio propagation model with limited interference (as the two-ray-ground model) or with ‘wide area interference’ (as with many non-deterministic models) is used. Following these lines, we make use of Nakagami’s distribution as radio propagation model. Actual measurements indicated that the Nakagami model fits better to VANETs than log-normal or pure Rayleigh shadowing. Again, the results for the Nakagami distribution show a difference to the one obtained with the two-ray-ground model: the effects of the priority access method can still be observed, however, the general level of probability of reception for prioritized and non-prioritized channel access is lower than for the case of the two-ray-ground model. With these results we get an understanding of what can be expected in real VANET environments. As a consequence, there is a strong need for enhanced mechanisms for robust and reliable exchange of information under realistic conditions. In particular, repetition and multi-hop retransmission strategies have to be incorporated to increase the probability of reception of a high-priority broadcast message.

The paper is structured as follows: in Section 2 we present some relevant related work. In section 3 some basic principles of 802.11 and the priority access mechanism is given. In Section 4 we outline our simulation set-up, the implementation of the 802.11a variant for vehicular ad hoc networks as well as the Nakagami radio propagation modeling. Results for a basic as well as a dynamic network scenario are presented in Sections 5 and 6, respectively. Section 7 provides our conclusions and some pointers to future work.

2. RELATED WORK

The various types of applications on top of a vehicular ad hoc network and their respective relative importance to each other gives rise to the question of how to prioritize certain data traffic over less important data. In [11] and [12] it is assumed that the radio technology is based on UTRA time division duplex (TDD) technology and the slots are grouped into a frame and super-frame structure. The first slot of a frame or super-frame is then reserved for high-priority data traffic. The mean channel access time depends on the length of the frame or super-frame. In contrast to [11] and [12] we look at a vehicular ad hoc network based on IEEE 802.11 technology since current work within DSRC working groups makes us believe that a variant of IEEE 802.11 is the most promising candidate for VANETs with respect to market introduction.

Recently, various papers on traffic differentiation in 802.11-based wireless LAN and ad-hoc networks have been published although most of them focus on improving some *unicast* flow performance in a congested medium. Already in 1999 the work [13] was published where Deng and Chang propose a priority scheme for the IEEE 802.11 DCF. This scheme is the basis of EDCA (Enhanced Distributed Channel Access) in the 802.11e draft [8]. Since 1999, a large number of research papers have been published using, evaluating or enhancing this methodology. For example, in [14], [15] and [16], the authors evaluate via simulation the EDCF mechanism, but only with respect to a few unicast streams (typical data-audio-video combination). There are some interesting analytical studies available that model the effect of the most important ECDF parameters, like [17], [18] and [19]. Unfortunately, in these papers the hidden terminal problem, which is an important issue in broadcast environments, is not considered at all or briefly. Another alternative on service differentiation can be found in e.g., [20], [21] and [22] where time is scheduled or reserved to improve, again, the performance of multi-hop communications with higher priority when the medium is saturated. These mechanisms, though, are invalid for emergency situations since there is no time available for establishing a sending order. The same reasoning applies for some other proposed EDCF improvements, e.g., [23] where a period of time is required to evaluate the channel conditions.

A different view to prioritization can be seen at [24], where the EPFL research group led by J.-P. Hubaux tries to detect nodes performing greedy misbehaviors at access points. These greedy nodes make use of ‘priority access methods’, although with a different intention.

3. PRIORITY ACCESS IN IEEE 802.11

3.1 Basic IEEE 802.11 mechanisms

The fundamental access method of the IEEE 802.11 MAC [5] is a distributed coordination function (DCF) known as a carrier sense multiple access with collision avoidance (CSMA/CA), see Figure 1. This medium access protocol states that when a frame arrives at the MAC layer to be transmitted the status of the channel must be checked. If the channel is idle at this point and during a DIFS (DCF Interframe Space) time interval the frame can then be transmitted. On the other hand, if the channel is busy, or becomes busy during that interval, the MAC will invoke the backoff procedure to reduce the probability of colliding with any other waiting station when the medium becomes idle again. A station performing the backoff process will wait until its Backoff Timer (BT) decreases to 0 to transmit. The BT value is chosen randomly from a discrete uniform distribution with values between 0 and CW (Contention Window) and can only start to be decremented after an idle DIFS interval. The backoff procedure will decrement its BT by 1 if no medium activity is indicated for the duration of a SlotTime, and will suspend the process if the medium becomes busy before reaching 0. The medium have to be idle for the duration of a DIFS period before the backoff procedure is allowed to resume.

After a transmitted frame a new backoff is performed even if there is no other frame waiting to be sent. This ”post” backoff ensures that the transmitting station will not have priority over any other waiting station, if any.

Two special considerations must be taken into account when focusing on broadcast messages. The first one is that there will not be any retransmissions and the value of the contention window

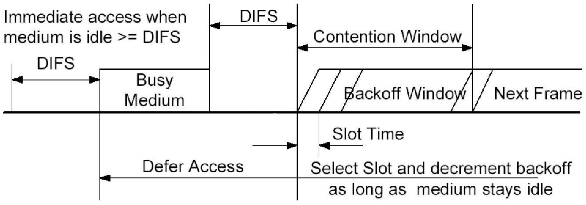

Figure 1: IEEE 802.11 basic access method

AC	CWmin	AIFS
0	aCWmin	2
1	aCWmin	1
2	(aCWmin+1)/2 - 1	1
3	(aCWmin+1)/4 - 1	1

Table 1: 802.11e priority parameters

CW will not be increased since there is no MAC-level recovery on broadcast frames. Second, the ready-to-send and clear-to-send (RTS/CTS) exchange is not used, therefore the hidden terminal problem exists. See Table 3 for the IEEE 802.11 parameters used in our simulations.

3.2 Priority access

The wireless LAN standard IEEE 802.11 proposes with its Enhanced Distributed Channel Access (EDCA) a way of providing differentiated channel access to data traffic with different priorities. We implemented the priority mechanism described in [8] focusing solely on transmission of broadcast messages and, therefore, without taking into account the proposed mechanisms for unicast communications. Our *ns-2* implementation provides four different types of traffic depending on its Access Category (AC). The prioritized traffic differs to the non-priority traffic ($AC = 0$) by using interframe spaces AIFSD[AC] and CW_{min}[AC] instead of standard DIFS and CW_{min}, respectively. The interframe spaces AIFSD[AC] are determined by

$$\text{AIFSD[AC]} = \text{SIFS} + \text{AIFS[AC]} * \text{SlotTime}$$

The values of AIFS[] and the corresponding contention windows for the different ACs can be found in the Table 1, and the SIFS (Short Interframe Space) and SlotTime used in our simulations can be found in Table 3.

The use of these values will prioritize the outgoing traffic of a particular node respect to the others in the medium, letting it access the channel with an shorter average time than the nodes with a lower AC.

Note that in our scenarios there is no Access Point present that is able to beacon all parameters, therefore, the above default priority values will be fixed for all nodes (Table 2 and 3).

4. SIMULATION SET UP

4.1 Scenarios

In our study we use two different scenarios, one with a static and one with a dynamic topology. The static one is used to deeply understand the impact of various protocol parameters under saturated channel conditions on the differences experienced by a node when using a higher priority in its transmissions. The static scenario consists of 600 cars placed in 8 parallel lanes of 4m width. The cars of each lane are separated by 20m from the following car. We make use of a deterministic radio propagation model, the two-ray-ground model, with a 200m communication range. Each node sends UDP packets of size 500 bytes every 100ms with a jitter of 10%. All nodes but one have an access category $AC = 0$ in all simulation runs. In this scenario we study the outgoing traffic of a specific car, placed approximately in the middle, that can have 4 different configurations described in Table 2.

AIFS	CWmin	AC
2	15	0
2	7	-
1	7	-
1	3	3

Table 2: Priority parameters of scenario 1

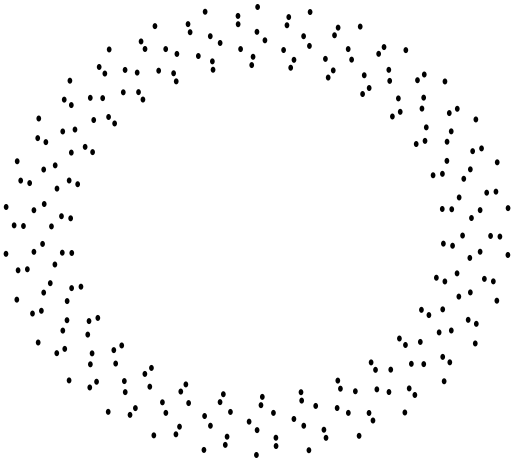

Figure 2: Circular 8-lanes highway (scenario 2)

Two of the configurations of Table 2 correspond to suggested values of [8]. The additional ones, varying the interframe spacing AIFS or the size of the contention window CW, were included in order to determine the direct impact of these parameters on the results and to understand their causes.

After the detailed performance analysis on the static scenario we focus on the second scenario, a more realistic dynamic scenario. Our main goal for this set of simulations is to perform a stress test in a medium-to-high car density scenario to study the possible effects and advantages that one could experience with the implementation of the priority mechanism. For this purpose we modeled an eight-lanes highway with four lanes per direction in a circular fashion (Fig. 2). Every lane is 4m wide and in order to avoid side effects the cars describe a circular trajectory. The radius of the inner lane is set to 350m in order to avoid interferences from nodes to the other side of the circle. In this first approach all lanes have the same number of cars, distributed uniformly along the circle, and all of them move at a constant speed without changing lanes, i.e. every car maintains the same distance between the car in front and behind during the whole simulation. To change the topology of the network along the time, all lanes have a different speed, assigned randomly with values between 55km/h and 120km/h. In all simulations, all cars have access category $AC = 0$ but one that has access category $AC = 3$ and is placed in the 6th lane (1st lane is the inner one). We study the

MAC	
CWMin	15
SlotTime	13 μs
CCATime	8μs
RxTxTurnaroundTime	2μs
SIFSTime	32μs
PreambleLenght	32μs
PLCPHeaderLength	8μs
PLCPDataRate	6Mbps
basicRate	6Mbps
dataRate	6Mbps
PHY	
CPThresh	6dB
CSThresh	-96dBm
RXThresh	-90dBm
bandwidth	6Mbps
freq	5.9GHz
Pt (100m)	93.85μW
Pt (200m)	375.4μW
Antenna	
Z	1.5m
Gt	4dB
Gr	4dB

Table 3: DSRC values used in our ns-2 modules

parameters described in Section 6.1 of two nodes in every simulation, the one with prioritized access and one without prioritization. As non-prioritized node we select the car in the 6th lane situated exactly at the opposite side of the prioritized one with respect to the circle's center. Thereby, we can compare two different priorities performances under the same conditions. We study different cases changing the following parameters: intended communication range (100m, 200m), packet size (200Bytes, 500Bytes) and radio propagation model. As propagation model, we either use the deterministic two-ray-ground model already implemented in *ns-2* or the non-deterministic Nakagami model. Since we are primarily interested in evaluating the behavior that all mechanisms would have in a real environment we decided to implement the Nakagami distribution, see Section 4.3.

4.2 5.9GHz 802.11 with 10 MHz channels

We introduced several changes to the *ns-2.26* MAC and PHY layer implementation. First, some bug fixing in some MAC functionalities was required to match the standard specifications. Second, all values have been adapted to be DSRC [1] compliant. As commented in Section 1, DSRC's underlying technology is based on IEEE 802.11a, although some minor changes are introduced, i.e. it works at the new spectrum available at 5.9GHz with 10MHz channels. This DSRC values and the decision of fixing the data rate to 6Mbps resulted in the modification of most of the PHY values of ns. Table 3 contains the changes using *ns-2* notation.

4.3 Nakagami Distribution

Several studies, e.g. [25], have demonstrated that the distribution of a signal amplitude x at a given distance in wireless channels can be well described by the two-parameter Nakagami distribution [26]:

$$f(x;\Omega,m) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} \exp\left[-\frac{mx^2}{\Omega}\right], \quad x \geq 0,\ \Omega > 0,\ m \geq 1/2$$

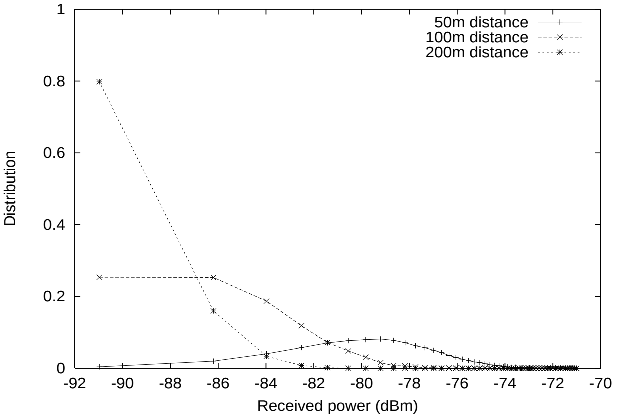

Figure 3: Distribution of received power at distances of 50m, 100m, and 200m to the sending node.

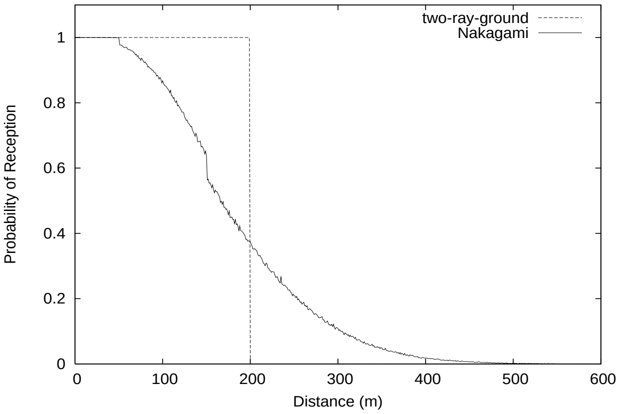

Figure 4: Probability of successful reception at distance d when no interferences are present.

where m is the Nakagami fading parameter and Ω is the average power at this distance. Note that m and $Omega$ depend themselves on the specific observed distance d, although we have not explicitely written it in the above formula for readability reasons. A detailed explanation of all steps necessary to estimate parameters m and Ω is out of the scope of this paper but we give some brief indication of the process to derive the parameters for a vehicular ad hoc network scenario. Empirical data from radios mounted on vehicles moving on highways was collected. In a moderate traffic condition one of the vehicles transmitted 200Bytes packets every 100ms (with 5.8GHz carrier frequency, 10 MHz bandwidth and 6Mbps) while the other vehicles were moving behind at various distances recording the values of received packet power and distance from the transmitter for each received packet. Afterwards, assuming the power values as the average of the packet power amplitude during the reception interval, a maximum likelihood estimation of m and Ω was performed. From the results obtained we approximate an average power Ω that decreases as d^{-2}, being d the distance to the sender, as expected from the average power in the deterministic models. On the other hand, we average the fading parameter m to 3 for low values of d ($<$ 50m) expecting line of sight conditions, decrease it to 1.5 for middle range distances, and make it match with a Rayleigh distribution, i.e. $m = 1$, for distances higher than 150m.

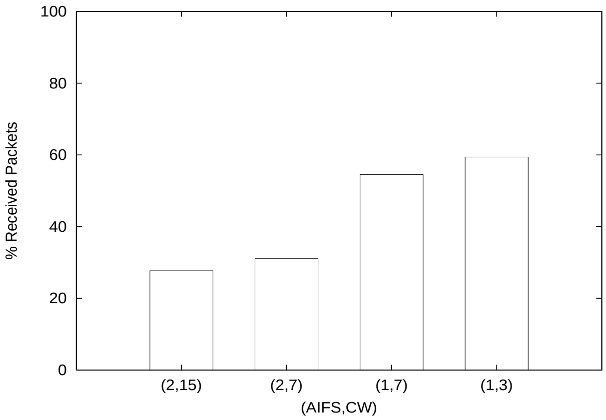

Figure 5: Scenario 1. Probability of reception for various (AIFS, CW)-settings.

Figures 3 and 4 represent the results obtained when setting our Nakagami *ns-2* implementation with the above parameters and using a sending power of -4.2dBm, that corresponds to a deterministic model's communication range of 200m. Figure 3 represents the received power distribution at 3 different distances (50m, 100m, 200m) and Figure 4 shows the probability of reception along the distance for both models in a scenario free of interferences.

5. BASIC SCENARIO

In order to get an insight into DCF performance in saturated conditions and in particular into the impact of the parameters interframe spaces AIFS and contention window size CW, we performed a set of simulations on the static scenario described in Section 4.1. In this scenario we study the packets sent by node S from the perspective of node R that is placed at a distance of 100m with respect to node S. This approach will allow us to analyze the conditions of the channel and the status of both nodes at the exact moment of sending or receiving a packet.

In Figure 5 one can see the effect of parameters AIFS and CW on the communication performance with respect to probability of reception. At a first sight, one can see that the parameter with greater impact is AIFS, which almost doubles the probability of success, and then we can see how a lower contention window improves results a little. However though, to fully understand the reasons that cause this improvements some more details are required.

Let us consider a saturated medium where during a channel busy period a high number of stations are waiting to send with a packet in their MAC, i.e., they have their backoff timer pausing. In this situation, all neighboring stations with same BT value will eventually collide, i.e., their packets will be sent at the same time to the channel and, therefore, not received correctly by any other node (up to the one that can make use of the 'capture effect'[2]). For a node with a smaller AIFS value, however, the situation changes since after every busy period it will start decrementing its backoff timer one SlotTime earlier than all the others (see Section 3.2). Thus, in certain conditions, this priority node will be able to access the channel earlier than all others, therefore sending without any chance to collide with any other node that can sense its signal on the channel. There are two situations from which the priority node can benefit:
- During a busy period it generates a packet and picks $BT = 0$. In this case no other node inside its carrier sense (CS) range[3] is able to collide with it, since they have to wait, at least, one slot more to start decrementing their BT.
- BT different than 0 is picked during a busy period and later the decrementing process is paused when $BT = 1$. In this case, the priority node will only be able to collide with nodes inside its CS range that generated a packet during this last busy period and, on top of it, picked 0 as BT value, which only happens with a very low probability.

AIFS/CW	RcvPkts	SntBT1	RcvBT1	SntBT0	RcvBT0
2/15	27.7%	69.3%	22.6%	5.8%	67.2%
2/7	31.1%	66.8%	22.1%	12.0%	66.6%
1/7	54.5%	46.4%	71.1%	11.9%	76.4%
1/3	59.4%	45.9%	71.0%	26.6%	78.9%

Table 4: *AIFS* and *CW* effect

To determine the real effect that the above conditions have in the results presented in Figure 5 the following metrics were defined:

- **RcvPkts:** Packets sent by node S that are successfully received by node R.
- **SentBT1:** Packets sent by node S after its backoff timer was paused with $BT = 1$.
- **RcvBT1:** SentBT1 packets that are successfully received by R.
- **SentBT0:** Packets sent by node S when $BT = 0$ was selected at the start of the backoff process.
- **RcvBT0:** SentBT0 packets that are successfully received by R.

As we can see in column SentBT1 of Table 4 most of the packets in our scenarios are sent after their backoff process is paused with $BT = 1$. This confirms the saturation condition of the channel where it is highly likely that a node can decrease only by one its BT in each channel idle period, before some other node accesses the channel. Column RcvBT1 shows the great impact that a shorter AIFSD has in this case: the probability of receiving successfully a packet is three times higher than without priority mechanism. To understand the impact of the contention window size CW, one should take a closer look at the two columns in the right. As we can see by RcvBT0, packets sent when choosing $BT = 0$ have the lowest probability of collision, as commented above, therefore, increasing the overall reception probability depending on their corresponding SentBT0 value. Obviously, the shorter the contention window size the higher the probability of picking $BT = 0$ when starting a backoff process (SentBT0).

Note that, as indicated in Section 3, we are operating in a broadcast medium, therefore the results are affected by the well known hidden terminal problem. This problem causes, e.g., that the number of received packets with a value for the BT of 0 (RecvdBT0) does not reach 100% when $AIFS = 1$.

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[2] The 'capture effect' can occur when two nodes that are within the communication range of each other send at the same time. In this situation, if another node R starts receiving the packet from the sender closer to node R a little earlier (consider propagation delay) with a power level at least a given SNR-value higher than the second one, the first packet can be successfully decoded.

[3] Carrier Sense range of a node S is the area where any other node would be able to detect that S is transmitting a packet although maybe not able to decode it.

6. DYNAMIC SCENARIO

With the insights into probability of reception under saturation conditions for the static scenario in mind, our goal is now to show results for a more realistic scenario, i.e., a scenario with vehicular mobility and with a more realistic radio propagation model. The setup described in section 4 represents a situation of medium-to-high data traffic load. In real life this scenario could correspond to the case where an emergency vehicle wants to pass or when one specific car has emergency messages to send. Again, we denote by S the observed sending node, when needed.

6.1 Studied Metrics

To quantify probability of reception and the benefit experienced with priorization we define these two metrics for the mobile scenario:

- *Channel Access Time*: Time elapsed since a packet is created at the application level until it is sent to the channel by the MAC layer.

- *Probability of Reception*: Percentage of cars that successfully received a packet considering all cars being at a distance *d±2.5m* from the sender at the moment that the packet is sent to the channel.

While channel access time is a standard metric in wired and wireless systems, we had to think the way to quantify the performance of a broadcast system. We propose this definition of probability of reception depending on the distance to the sender because in our system we consider every packet to be intended to be received by all cars in a certain area around the sender. With this parameter we can then define a certain maximum distance where, if crossed, packets would not be received with a specific probability value.

6.2 Simulation Results

It is obvious that the behavior of any protocol highly depends on the channel load. Usually, saturated environments provide a challenge for every protocol. We have chosen two sets of parameters (200 and 500 bytes packet sizes, 100m and 200m intended communication ranges) resulting in four scenarios with different load conditions to give a reasonable representation of the conditions one could find in real life. With respect to the size of the packets, 200B would represent a simple application packet, and 500B could apply to a more sophisticated system including, e.g., some kind of security elements. We chose 100 and 200 meters as intended communication ranges. Of course, we could easily think about many situations were it would be helpful to warn cars at a much higher distance, however, that would even increase the data traffic load on the shared medium. Our simulations are based on a highway with four lanes per direction and a car every 20 meters in every lane sending 10 packets per second. Our most saturated scenario, considering a deterministic propagation model, would have approximately a load as given by the following expressions:

$$\frac{8[\text{lanes}] * 400\text{m}[\text{com.diameter}]}{20\text{m}[\text{between cars}]} = 160[\text{cars/com.range}]$$

$$160[\text{cars}] * 10\text{pkts/s} * 500\text{B/pkt} * 8\text{bits/B} = 6.4\text{Mbps}$$

These results mean that we have a generated traffic of 6.4Mbps in a 6Mbps channel, without considering the 28 octets of the MAC header nor PHY preambles. This 'channel load' is not, however, the highest we could find, just think of a highway with a traffic jam just after an accident, or a street intersection in NY city during rush hours.

Scenario			**Channel Access Time**	
Com.Range	**Pkt Size**	**Load Mbps**	**Priority**	**Non-Priority**
100m	200B	1.28	0.4ms	0.9ms
100m	500B	3.2	1.6ms	4.8ms
200m	200B	2.56	1.2ms	3.9ms
200m	500B	6.4	3.6ms	16.4ms
200m (Nak)	500B	6.4	9.0ms	26.5ms

Table 5: Channel Access Time

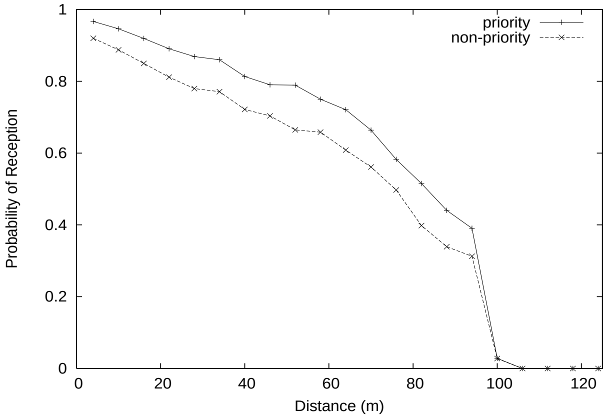

Figure 6: Probability of reception for the case of 100m communication range and 500B packets.

All results presented in this section have been computed from the data obtained from running the scenarios commented above during 60s of simulated time. Each of these runs took up to 9 hours[4] and generated about 5GB of data, which needed more than 3 hours to be parsed with our scripts.

Table 5 shows the *Channel Access Time* for the different scenarios. It can be observed how the node with priority outperforms in all cases the non-priority one, as expected, being this delay 4 times smaller in the most saturated case. The non-deterministic scenario (200m 500B Nak) will be commented later in this section.

Figures 6, 7, 8 represent the results of the simulations using the deterministic two-ray-ground as radio propagation model. We can see a higher probability of reception for the priority node, being more noticeable when the overall channel load is higher. While the differences between prioritized and non-priority nodes might not seem large in Figures 6 and 7, averaged over distance the priority curve is 9.6% and 16.3%, respectively, higher than the results for the non-prioritized nodes. This difference goes up to 150% in the most congested scenario.

Note an interesting effect in all six curves with respect to the hidden terminal problem. The probability of reception decreases with a higher slope for distances to the sender higher than 66% of the intended communication range. Essentially, at this distance interferences from the hidden terminals, i.e., nodes that are outside of the carrier sense range of our sending node S but close enough to the border to cause interferences, will start to be observable. Packets sent by these hidden terminals can only collide with packets sent by S in area where the difference between the packets' power level is lower than the required SNR i.e., farer than 66m in the case of 100m communication range and 132m in the case of 200m. Additionally,

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[4] Our simulation machines are 3.2GHz Pentium IV with 1GB RAM.

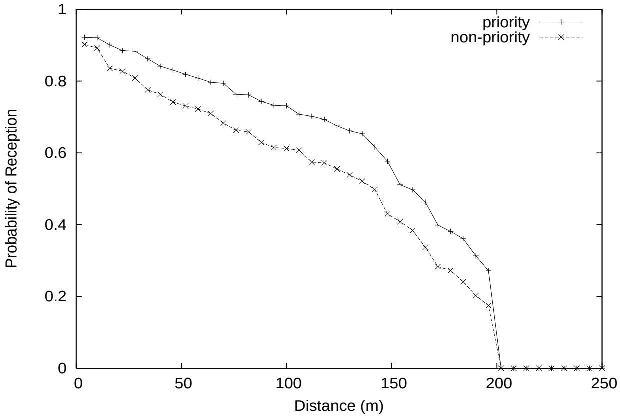

Figure 7: Probability of reception for the case of 200m communication range and 200B packets.

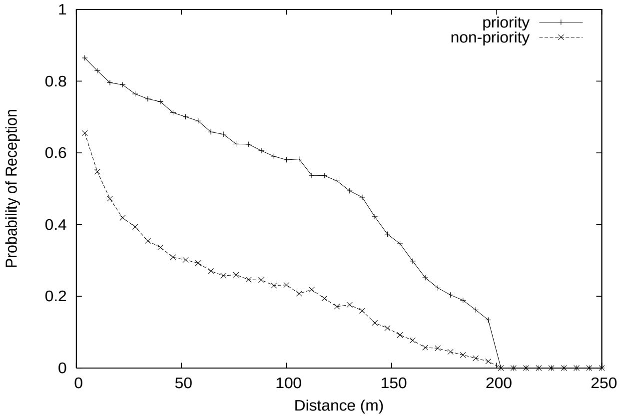

Figure 8: Probability of reception for the case of 200m communication range and 500B packets.

one can see in Figure 8 how the congestion of the channel differently affects the two types of nodes. The values of the priority car keep relatively high while, on the other hand, the non-priority ones drop drastically in the first few meters. This again can be explained considering the 'capture effect' and the 6dB SNR used in our implementation. Note that the amplitude of the power decreases as d^{-2}, so, to have a difference of 6dB corresponds to be at double distance. In other words, if the receiver node is at a distance d_1 of the sender and d_2 of the interferer, it will be able to successfully receive the packet of the first one only if $d_1 {\leq} (d_2/2)$. Considering now that we are in a road scenario, the number of nodes, i.e., potential colliders, inside a circular area increases 'quadratically' with its radius only within the first meters, then it will increase linearly. This phenomenon, tough, does not affect the same way to the priority node since its chances of sending one slot earlier than all the others is pretty high, as explained in Section 5.

In order to increase the degree of 'realism' we re-run the simulation with a non-deterministic radio propagation model, the Nakagami model outlined in Section 4. Figure 9 shows the results obtained with the Nakagami model for the case of 200m communication range and 500B packet size. Comparing Figure 8 with Figure 9 and the values in the last two rows in Table 5 we can see how the use of a more realistic radio propagation model degrades the probability of reception and channel access time of both types of nodes, the non-priority and the priority ones. To us, these results are interesting since they quantify how signal power fluctuations can seriously affect the performance of a protocol and in particular, in our case, the probability of reception and channel access time of 802.11 and the prioritization mechanism.

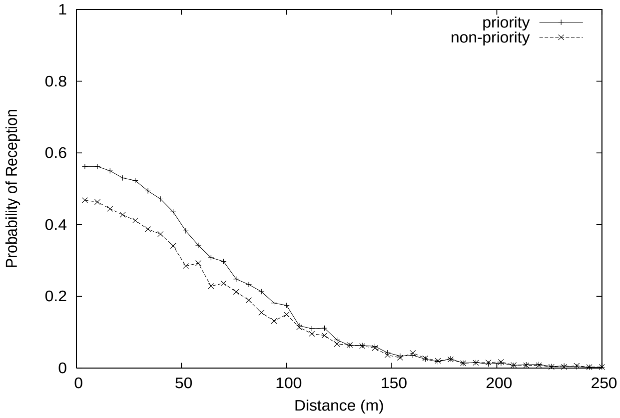

Figure 9: Probability of reception for the case of 200m 'average' communication range and 500B packets under the Nakagami radio propagation model.

The first thing to take into consideration when trying to understand the obtained results is the 'heavy-tail' property of the Nakagami distribution (see Figure 4): frequently, nodes are interfered by nodes farther away than with the deterministic two-ray-ground model. On the other hand, frequently cars cannot decode (or even sense) the messages sent by other cars inside their "intended" communication range. Taking into account the commented property one could already expect a performance degradation of the probability of reception of both types of cars. However, it is still not so clear why the impact on the priority ones is much worse or why nodes experience a longer channel access time. Therefore, in order to have a clearer picture of the channel conditions and the causes that make the observed nodes suffer from degraded performance we have checked two additional parameters:

- *Sensed Packets per second (Sens. Pkts/s)*: Average number of packets per second that arrive at the observed node S with power greater or equal than the *Carrier Sense Threshold*.
- *Channel Idle Time Ratio (Ch. Idle Time)*: Time ratio, over the whole simulation, that the observed node S senses the channel as idle, i.e., it cannot sense any packet in the channel with power greater or equal than the *Carrier Sense Threshold*.

In Table 6 we show this 2 new parameters and again the channel access time (Ch. Acc. Time) for both propagation models, two-ray-ground (TRG) and Nakagami (Nak), to get some more insight in the effect that the later model has on the two types of nodes. As we already noticed in Table 5, the nodes on the Nakagami scenario require a longer channel access time. Considering the above commented 'heavy-tail' property one could easily think that the non-deterministic model could result in a higher number of packets being sensed by the observed node S, resulting in a busier medium and therefore in a longer channel access time. If we take a closer look at Table 6 though, we can see that this is not the case since nodes in the two-ray-ground scenario sense in average 7% more packets in their radio interfaces over time. The third parameter

Scenario (200m,500B)	Priority		Non-Priority	
	TRG	Nak	TRG	Nak
Ch. Acc. Time	3.6ms	9.0ms	16.4ms	26.5ms
Sens. Pkts/s	3325.2/s	3093.2/s	3324.6/s	3096.8/s
Ch. Idle Time	10.8%	4.4%	10.6%	4.4%

Table 6: Nakagami Effects: comparison of channel access time, number of sensed packets per second, and channel idle time between two-ray-ground model (TRG) and Nakagami model (Nak).

on the same table, *Ch. Idle Time*, however, shows that the channel in the Nakagami scenario is actually more busy, i.e., over longer periods of time. We can deduce then, that in the case of using a non-deterministic radio model the sensed packets in the medium are distributed over time in such a way that keeps the channel busy during longer periods of time although the quantity of packets is lower in number. This explanation matches with the idea of being in a scenario where collisions no longer occur mainly for the reason of having the same backoff timer value BT as a neighboring node. Instead, by not being able to sense packets already on the channel and sending packets when one's own backoff timer BT decrements to 0, a collision might occur since a packet from a neighbor is still on the channel. Clearly, in such conditions the chance of accessing the channel earlier than non-priority nodes does not give the same benefit than before with the deterministic two-ray-ground model.

One must take in consideration when looking at Figure 9, though, that no temporal or spatial correlation was studied and applied to the Nakagami distribution. Thus, each node 'selects' its received power level independently of the other nodes around.

7. DISCUSSION, CONCLUSIONS AND FUTURE WORK

In this paper we have investigated the topic of sending broadcast messages to a vehicle's neighbors as the basic communication primitive for VANETs. The studied scenario differs from other 802.11 service differentiation scenarios since it does not look to a single cell scenario with unicast traffic, but to an ad hoc network scenario with broadcast traffic. As a measure of success, we have proposed 'probability of reception' in dependence of the distance to the sender as a reasonable metric to gain a fundamental understanding of VANETs and to study effects of prioritization and received power fluctuations within an 802.11-based vehicular ad-hoc network.

In general we can assume that when VANETs become successfully deployed, the network will most of the time operate in a state of saturation. Thus, one has to address the challenge of network stability and reliable reception of important messages. We have analyzed in detail a priority access mechanism based on ideas of the 802.11 EDCA mechanisms for two-ray-ground and Nakagami radio propagation models. First, we were able to demonstrate that large gains can be achieved for a prioritized node with the proposed mechanisms under the two-ray-ground model in a saturated scenario. We have shown how the parameters can be tuned to reduce the chance for collision. Second, we observed that for the non-deterministic Nakagami model the probability of reception is reduced for both, non-priority and priority nodes, being worse for the first one. From these contributions some important conclusions and items for future work can be derived:

- *Probability of reception.* Under saturation conditions the probability of reception of broadcast messages can be as low as 20%-30% at distances of 100m to the sender and even lower for larger distances. Thus, when reliable reception of broadcast messages is required, priority access methods, relay/repetition strategies or reservation schemes appear to be essential.

- *Priority access*. With respect to the metric 'probability of reception', a priority access method only pays off under a saturated medium. However, with respect to channel access time, it always allows a quicker access to the medium compared to non-prioritized nodes.

- *Realistic radio models*. While emphasized for quite some time, realistic radio models are still rarely used in ad hoc network simulations. Our results show the significant effects of using a non-deterministic radio propagation model compared to the standard use of unit disc graphs. Still, more effort is required in this direcction, like elaborating specific models for different scenarios and studying the benefit of using better reception techniques, e.g. antenna diversity.

- *Degree of 'synchronization'*. With a non-deterministic radio propagation model, the degree of synchronization of the various stations appears to be less strong as in the case of the deterministic two-way-ground model. Thus, the number of 'hidden node incidents' is increasing. Currently we are working on formalizing this argumentation.

- *Topology control*. Adjusting the sending power can be used to adjust the number of neighbors that will be receiving the message. However, most topology control mechanisms assume deterministic, i.e., unit disc graph compliant radio propagation models. With our results one can see that the sending power has to be adjusted in order to achieve a certain probability of reception at a specific distance. However, this also results in interferences with other nodes on a much wider range.

- *Spatial and temporal correlations*. As mentioned in Section 6, we are currently not making use of mechanisms for spatial and/or temporal correlations with respect to non-deterministic received signal power strength. To the best of our knowledge, no measurement data for vehicular ad hoc networks exist that can help to determine the right degree of correlation.

- *Retransmission and relay strategies*. Since a reliable reception of important messages will be an important feature of VANETs, we plan to study how to tune retransmission and multi-hop relaying strategies to improve probability of reception.

- *Mobility, one dimension vs two dimensions, radio fluctuations*. When comparing our results for our two scenarios, the question arises which factor — mobility, dimension, or radio fluctuations — is mainly responsible for the observed behavior. Additional simulations with the Nakagami model in a one-dimensional setting without mobility yield essentially the same results as for the two-dimensional case with mobility. Thus, mobility as well as the circular setting do not have a similar effect as the use of the (realistic) Nakagami distribution has compared to a deterministic two-way-ground model. In [27] we show that in certain cases radio fluctuations can add more 'mobility' to a scenario than node mobility does.

- *Traffic modeling.* A good insight into future applications of VANETs is needed in order to improve modeling of data traffic with respect to packet generation.

We plan to continue this work along these lines including an analysis of two and more prioritized nodes and under improved mobility models.

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