802.11p: Insights from the MAC and Physical Layers for a Cooperate Car Following Application

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Abstract. We present a simulation study of a cooperate car following application implemented by the Wireless Access for Vehicular Environments (WAVE) protocol stack, which uses the MAC and Physical layers defined by the IEEE 802.11p protocol. This is a simple Intelligent Transportation Systems (ITS) application which forms the foundation for autonomous driving. As with many safety-critical ITS applications, cooperate car following uses beaconing as the primary means of communication. The beacon frequency and the transmit power of the mobile nodes are considered as the key communication parameters, while the vehicle density is considered as the key traffic parameter. The two main factors affecting the performance, the end-to-end delay and the packet loss, are studied for different scenarios defined by the above parameters. Results indicate how the application performance may be improved by adapting the beacon frequency and/or the transmit power according to the vehicular traffic density.

Keywords: Vehicular ad-hoc networks · WAVE · IEEE 802.11p DSRC · VEINS · SUMO · OMNET++ · Autonomous driving Intelligent Transportation Systems

1 Introduction

The rapid growth of vehicle traffic is a major concern worldwide. Intelligent Transportation Systems (ITS) are envisioned to alleviate this concern through utilizing Information and Communication Technologies (ICT). Autonomous driving, which is of much interest today, is also enabled by ITS. We use a simulation based approach to draw insights on the performance of cooperative car following in an autonomous driving scenario.

ITS applications vary from automated vehicle handling to infotainment. These applications can be viewed as safety and non-safety applications [1].

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In most ITS safety applications, reliability and low latency in communication are the most critical requirements. The IEEE 802.11p standard [2], which implements the physical and Medium Access Control (MAC) layers of the Wireless Access in Vehicular Environments (WAVE) protocol stack, is designed to cater to these requirements within highly dynamic vehicular networks [3]. WAVE, which is also known as Dedicated Short Range Communication (DSRC), uses 75 MHz in the 5.9 GHz band, with one Control Channel (CCH) and six Service Channels (SCH).

Rapid changes in the topology of vehicular ad-hoc networks (VANETs) necessitate each vehicle to have an understanding on the entire vehicular topology within ones transmission range. In IEEE 802.11p, periodic one hop broadcasts (*beacons*) are used to disseminate regular updates on the state of each vehicle. Updates include position, velocity, acceleration etc. Thus, all applications contain an underlying beaconing process. Also, there are messages that are triggered by certain events (*event driven messages*). In applications where both event driven and beaconing messages coexist, beaconing can congest the channel, and disrupt event driven messages [4]. Low beacon frequencies hinder timely transmission of status information, while high beacon frequencies congest the network, increasing delay and packet loss. Thus, the beacon frequency has a direct impact on the performance of ITS applications. In this paper, we focus on this important parameter, on a cooperative car following application.

The study in [5] presents analytical and simulation results on the delay and throughput of the IEEE 802.11p protocol, with emphasis on the MAC layer characteristics. In [6] the packet loss probability related to the protocol is studied, focusing on the loss caused by the WAVE channel switching between the CCH and the six SCHs. The performance evaluation of IEEE 802.11p presented in [7] is the most related to our work as it focuses on the performance of the protocol with respect to the beacon frequency, and its effect on reliability, delay and scalability of the network. The analysis in [8] presents the effect of transmit power on the packet loss and highlights the necessity of power control in improving ITS application performance.

While general analyses of the IEEE 802.11p protocol are provided in the above studies, the focus of this paper is a specific application, which provides some useful insights on the effect of the beacon frequency on its performance. Since cooperative car following is the basic application where beaconing is used, it is chosen for our study.

In the cooperative car following model, changes in the motion of the leading vehicle are communicated via beacon messages, and the lagging vehicle adjusts its acceleration to avoid a collision. Delay and packet loss are two of the most critical parameters that will affect the performance of this application. A packet being lost or delayed causes slow reactions from the lagging vehicles, and faulty acceleration calculations, which may cause the vehicles to collide. We have carried out simulations to study the maximum tolerable packet loss levels to avoid such collisions. Among the simulators that can be used for VANETs [9], VEINS, which integrates SUMO and OMNeT++ by coupling them bi-directionally through the TraCI Scenario Manager, is considered to be suitable for such a study [10,11], and is hence selected.

In Sect. 2 of the paper, we introduce the topological and communication models, and give an overview on packet losses and delays in the IEEE 802.11p protocol relevant to our application. Section 3 introduces the simulation environment, the simulators used, issues encountered and how they are resolved. Simulation results and their analyses are presented in Sect. 4 highlighting some key insights obtained. Section 5 concludes the paper.

2 System Model and Problem Formulation

2.1 Topological Model

As shown in Fig. 1, there are multiple vehicles, in N lanes. Consider two successive nodes in the chain. We call the vehicle at the front, the leading vehicle (LDV), and the vehicle that is following, the lagging vehicle (LGV). Let v_1, v_2 and a_1, a_2 denote the velocities and the acceleration of the LDV and LGV, respectively. d denotes the gap between the vehicles. The vehicular traffic density can be varied by changing N and d. Each vehicle in the chain travels at the maximum possible velocity $v_{\max}$ along the highway, and maintains a safe distance d_s with the LDV. If the LDV decelerates at the maximum possible deceleration and stops, the LGV can also decelerate at its maximum deceleration, and stop with a safety distance of d_0 between them (we have $d_0 \leq d \leq d_s$). Accordingly, if one vehicle in the chain stops suddenly, all following vehicles should be able to stop safely without a collision. Also, when the vehicle that stopped first starts moving again, all vehicles should start moving and reach $v_{\max}$ again. Thus, the LGV will continuously adapt its behavior to that of the LDV.

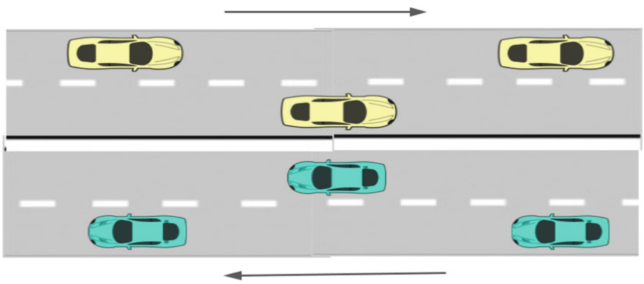

Fig. 1. Topological model.

Two scenarios of interest can be identified. Firstly, if the LDV decelerates and stops, the LGV sets its acceleration to

$$a_2 = \frac{v_2^2}{2(x_1^d - d_0 - d)} \tag{1}$$

for each received beacon, where x_1^d is the distance traveled by the LDV before stopping.

Secondly, we consider that the LDV accelerates again to reach $v_{\max}$. If the distance traveled by the LDV and the LGV to reach $v_{\max}$ are x_1^a and x_2^a respectively, we have $x_2^a + d_s = x_1^a + d$, and

$$a_2 = a_1 \frac{(v_{\max} - v_2)^2}{(v_{\max} - v_1)^2 + 2a_1(d_s - d)}. \quad (2)$$

After the LDV reaches $v_{\max}$, the acceleration of the LGV should be

$$a_2 = \frac{(v_{\max} - v_2)^2}{[2(d_s - d)]}. \quad (3)$$

2.2 Communication Setup

In order to adapt their velocities in this manner, vehicles broadcast information such as their ID, position, lane, speed, and acceleration. This is achieved through periodic beacon messages. Since these beacons are important only to the vehicles within the immediate surroundings of the sender, they are not forwarded, and only single hop transmission of beacons is used. Messages are created as Wave Short Messages (WSMs), which are sent through Wave Short Message Protocol (WSMP), and are broadcast in the IEEE 802.11p beacon frame over the CCH of DSRC. Vehicles adjust their acceleration based on the beacons from the preceding vehicle.

2.3 Channel Modeling

In order to understand the application level performance at the most fundamental level, we assume that the communication is only impaired by path loss. For this, we use the simple path loss model, with a path loss exponent of 2. Next, we add fading by using the Nakagami fading model, which is considered to be the most suited for the VANET environment [12]. Under this fading model, the probability density function of the received signal amplitude is given by

$$f(x : m, \omega) = 2\frac{m^m}{\Gamma(m)\omega^m} x^{2m-1} \exp^{-\frac{m}{\omega}x^2}, \quad (4)$$

where m is the fading depth parameter, ω is the average power and $\Gamma(\cdot)$ is the Gamma function.

2.4 Performance Measures of Interest

Packet loss and delay are the most important parameters that hinder the performance of a VANET. The packet loss is defined as the difference between the number of successfully received packets and the number of transmitted packets. According to the IEEE 802.11p physical layer, received beacons are discarded due to (i) the received power level being below the receiver sensitivity

(ii) the received signal-to-interference-plus-noise ratio (SINR) being below the SINR threshold (SINR loss) and (iii) beacons being received while transmission is ongoing (TX/RX loss)

End-to-end delay is defined as the time taken for the reception of a packet at the application layer of the receiving node from the time it originated at the application layer of the sending node. According to [13], it consists of the three components;

- the waiting delay, which is the duration between the time the WSM is generated at the application layer to the time it is transmitted into the channel. This is caused by the backoff process within the MAC layer of the IEEE 802.11p protocol.
- the transmission delay, which mainly depends on the size of the packet. The effect of frequency on the transmission delay is considered to be negligibly small.
- the retransmission delay, which is not considered in this paper since WSM messages are not acknowledged and retransmitted.

2.5 Problem Formulation

We study the effect of the beacon frequency on the end-to-end delay and the packet loss in the network. Moreover, since the application is highly dependent on proper communication between vehicles, our objective is to identify maximum levels of delays and packet loss that can be tolerated in the network while maintaining successful operation without any collisions. The beacon frequency has a direct impact on these performance measures, which we attempt to understand through simulations.

3 Algorithm Implementation and the Simulation Environment

3.1 Message Processing Algorithm

The received messages need to be filtered before processing. Each packet contains information such as node ID, position, lane ID, distance between transmitter and receiver etc. Only the messages from the immediate LDV need to be processed, and this is done by identifying the node ID and the distance to the neighbor. Process followed by each node is presented in Algorithm 1 (Table 1).

3.2 Simulation Environment

The simulators that we use are SUMO, as the traffic simulator, and OMNeT++ as the network simulator. VEINS is selected as the simulation platform, which is an integrated VANET simulation software that couples SUMO and OMNeT++, bi-directionally.

Table 1. Message processing algorithm

```
a_max ←maximum acceleration
Packet reaches the application layer
if TX lane ID == RX lane ID then
    if TX node ID == Neighbor node ID then
        calculate acceleration a_2
        if a_2 < a_max then
            acceleration ← a_2
        else
            acceleration← a_max
    else
        if distance to TX<distance to neighbor then
            Neighbor node ID←TX node ID
            distance to neighbor←distance to TX
            Go to 5
        else
            Stop Processing
else
    Stop Processing
```

SUMO Implementation. SUMO is used to create the road network. Parameters related to vehicles such as maximum acceleration, maximum deceleration, maximum speed, the number of vehicles and gaps between vehicles (vehicle density) are defined within SUMO. SUMO contains its own car following model which cannot be disabled. It is also a collision free traffic simulator. However in this study, it is required that the movement of vehicles is controlled by our cooperative car following model instead of SUMO's inbuilt one. To achieve this, firstly, the "Mingap" parameter in SUMO, which indicates the minimum gap that is maintained between two vehicles when the velocity of each reaches zero, is set to zero. This enables collisions. Next, the parameter "tau", which indicates the time headway, is set below the simulation step size. This enables collisions when our cooperative car following model fails.

OMNeT++ Implementation. The network simulation is implemented in OMNeT++. A WSM is prepared including information such as speed, acceleration, lane ID, Node ID and position of the sender. These parameters are retrieved from SUMO with the aid of TraCI Scenario Manager in the OMNeT++ mobility module. On receiving the beacons, vehicle nodes are programmed to adjust their acceleration/deceleration based on the information within the beacon. TraCI commands are then issued back to SUMO to set the acceleration of the vehicles accordingly.

Parameters such as packet loss, channel busy times etc. are recorded as scalars, while speed, accelerations, position of each vehicle are recorded as vectors. These statistics are used to study the performance of the application for different simulation settings.

4 Simulation Results

To analyze how the application performance can be optimized, simulations were carried out by enforcing parameters as follows: Tx power 20 mW, Receiver sensitivity −89 dBm, Thermal noise power −110 dBm, Carrier frequency 5.89 GHz, Maximum Speed 100 km/h (27.78 m/s), Maximum Acceleration 2.5 m/s^2, Maximum Deceleration & 4.5 m/s^2. Different beacon frequencies are studied. In order to simulate different traffic densities, two different values, 7 m and 12 m are chosen for d and three different values for N, 1, 2 and 4.

4.1 Effect of End to End Delay

The results for end to end delay are presented in Fig. 2. Sample size varied based on the beacon frequency, the gap between vehicles and number of lanes used. Minimum number of samples were generated at 10 Hz and 50 vehicles on a single lane, leading to about 250000 delay values. Different beacon frequencies are simulated for $d = 7$ m and $d = 12$ m. It is seen that as the vehicle density increases, the delay increases. This is due to the increase of the contention delay in the MAC layer. However, this increase is of the order of several milliseconds. The minimum delay required for the application to fail, as determined from equations of motion for $d = 7$ m and 12 m, turn out to be 0.25 s and 0.45 s respectively. Thus, it can be concluded that in the cooperative car following scenario, the effect of the end to end delay on the performance of the application is negligible for practical beacon frequencies and node densities.

The reason for this can be rationalized via the improvements done to the MAC layer of IEEE 802.11p. In IEEE 802.11p, when a packet arrives, it is immediately forwarded to the channel if the channel has been idle for a time period more than DCF Interframe Space (DIFS) + backoff × slot length, unlike in conventional CSMA/CA, where a period amounting to DIFS is waited irrespective of the channel state. The backoff is randomly selected from an interval between $[0, CW]$ where CW is the size of contention window. Also, in IEEE 802.11p, CW is not increased once a backoff is done, which is the case in conventional CSMA/CA. Alternatively, the backoff value that was set for a particular packet is decremented by one if channel becomes idle for a period of DIFS. This mechanism has allowed packets to be transmitted with less waiting delays.

4.2 Effect of Packet Loss

The variation of packet loss with beacon frequency is illustrated in Figs. 3 and 4 for $d = 12$ m and 7 m respectively. The maximum tolerable packet loss (MTPL) is found by artificially inducing a random beacon drop, and increasing the probability of dropping until the application fails. Failure can be observed by two vehicles colliding with each other in the SUMO GUI, or by inspecting velocity, acceleration and position graphs generated by OMNeT++. In the plots, we have chosen the highest packet loss percentage for which the application is successful more than 70% of the time, as the maximum tolerable packet loss.

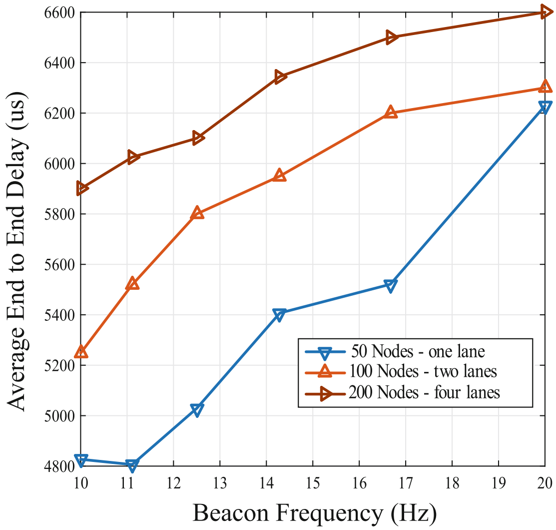

Fig. 2. Average end to end delay for different beacon frequencies.

The MTPL line represents the boundary between failure and operational regions. Any point above this line is a failure. We observe that the MTPL increases with the beacon frequency. This is an advantage of increasing the beacon frequency. The maximum tolerable packet loss also increases with the gap between vehicles, which is intuitive.

It is interesting to note that the application fails if the beacon frequency is lower than a certain value. This minimum beacon frequency decreases as d increases. Thus, beyond this lower limit, the LDV will not be able to notify the LGV in time. We are therefore able to gain insights into the range of beacon frequencies which would make the application operate successfully in different road traffic conditions.

The packet loss ratios for different vehicle densities and beacon frequencies are also illustrated in Figs. 3 and 4. The simple path loss model is used for the simulations. We observe that when the beacon frequency increases, the packet loss increases, and at a certain point, enters the region of failure. This is because frequent transmission leads to more SINR and TX/RX losses. Thus we conclude that increasing the beacon frequency has its disadvantages as well.

We also note that the packet loss increases with the vehicle density. This is due to increased interference. At lower vehicle densities (higher d) the packet loss ratio is low. This means that the network is interference dominant. To illustrate further, when $d = 7\,\mathrm{m}$, the application will not work at all for two lanes, but when $d = 12\,\mathrm{m}$, it works for all considered beacon frequencies except 20 Hz. This means that, if a vehicle traveling along a single lane road approaches one with two lanes, a roadside unit should inform vehicles to either decrease the beacon frequency, or to increase the safety gap.

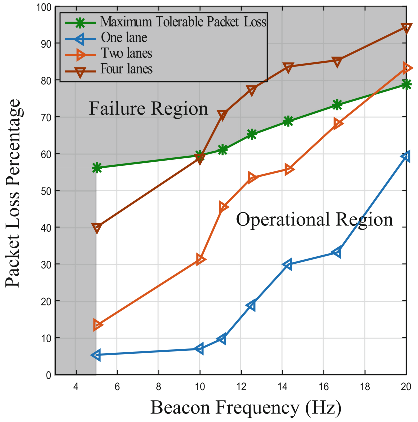

Fig. 3. Regions of success and failure, $d = 12$ m.

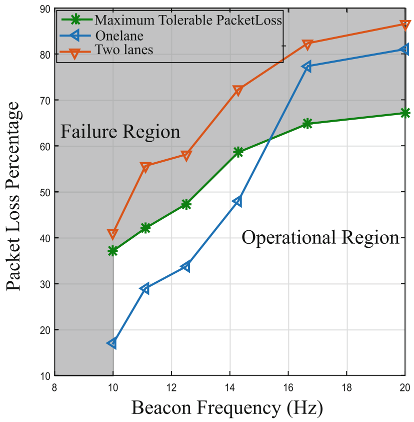

Fig. 4. Regions of success and failure, $d = 7$ m.

Next, we study the packet loss in the presence of Nakagami fading. Results are illustrated in Fig. 5. Here, the fading depth parameter is set to one, which represents the most severe fading environment. Thus, Fig. 5 represents performance bounds by presenting the best case and the worst case in terms of fading, and our expected achievable performance should lie within these bounds. It is noteworthy that when the vehicle density is high, the two bounds are comparatively close.

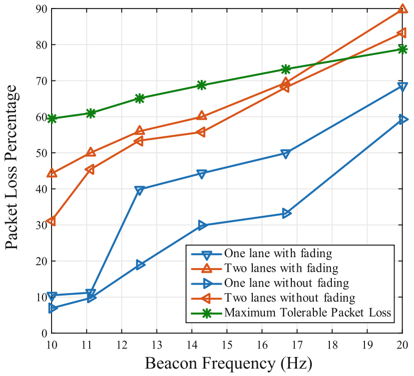

Fig. 5. The effect of fading on the packet loss, $d = 12$ m.

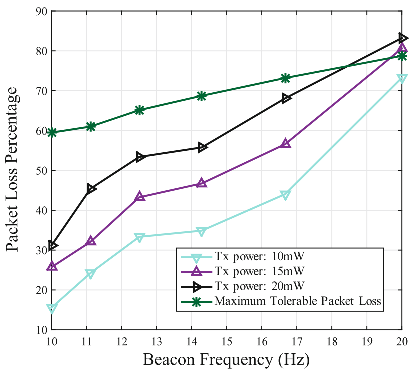

Fig. 6. The effect of transmit power on the packet loss, $d = 12$ m.

Figure 6 shows the packet loss for different transmit power levels. The packet loss decreases with decreasing transmit power. This is because lowering the power decreases interference, which leads to lower SINR losses. Extrapolating this behavior to the $N = 2$ line in Fig. 4, it may be possible to bring this into the operational region, by reducing the transmit power. This result provides preliminary insights into possible advantages of adaptive power control in changing traffic scenarios. However, reducing the transmit power will have adverse effects in a low traffic density scenario, where the nodes are far apart. Optimizing the transmit power considering these opposing effects will be looked at in future.

5 Conclusions

We have evaluated through simulations, the performance of a cooperative car following application based on the beacon-broadcasting process of the IEEE802.11p protocol.

The two main factors affecting the performance of this application, the end-to-end packet delay and the packet loss have been studied for different vehicular traffic densities.

Results demonstrate that the end to end delay of IEEE 802.11p is insignificant under practical vehicle densities and beacon frequencies, and that packet loss is the principal cause for application failure. Bounds within which the application performs successfully have been identified. We have also shown that the application performance may be improved by adaptively changing the beacon frequency and/or the transmit power as the vehicle density changes.

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