Dimensioning Wave-Based Inter-Vehicle Communication Systems for Vehicular Safety Applications

Miguel Sepulcre
Signal Theory and Communications Division
University Miguel Hernández
Elche, Spain
msepulcre@umh.es

Javier Gozalvez
Signal Theory and Communications Division
University Miguel Hernández
Elche, Spain
j.gozalvez@umh.es

Abstract— **Inter-vehicle wireless communication systems are currently being developed as a promising technology to improve traffic safety. Considering their decentralized nature, its deployment faces important challenges to guarantee an efficient and reliable transmission of broadcast safety messages. This paper investigates the dimensioning of such systems by analysing the impact of key operating conditions on its performance. The final aim of this investigation is to identify efficient radio resource management techniques for inter-vehicle wireless systems.**

Keywords-component: wireless vehicular communications, system dimensioning, radio resource management.

I. Introduction

Wireless vehicular communications have been identified as a promising technology for deploying Intelligent Transportation Systems aiming at improving traffic safety, efficiency and quality [1]. To address the technical challenges of inter-vehicle wireless communication systems, different worldwide research initiatives have been launched in the past years. In the US, the American Society for Testing and Materials (ASTM) developed the Dedicated Short Range Communications (DSRC) standard based on IEEE 802.11a [2]. The US Department of Transportation also launched the Cooperative Intersection Collision Avoidance Systems (CICAS) initiative aimed at addressing the full set of intersection crash situations through a combination of autonomous-vehicle, autonomous-infrastructure and cooperative communication systems [3]. The European Commission has also recently launched the *eSafety* initiative within the FP6 work program, to accelerate the development, deployment and use of Intelligent Integrated Safety Systems using Information and Communication Technologies (ICT) to increase road safety [4].

To exploit the potential of inter-vehicle wireless communications, the IEEE is currently developing an amendment to the IEEE 802.11 standard (IEEE 802.11p), usually referred as Wireless Access in Vehicular Environments (WAVE) [5]. The WAVE proposal is based on seven, ten-megahertz channels consisting of one Control Channel and six Service Channels in the 5.9GHz band. While the service channels are used for public safety and private services, the control channel is used as the reference channel to initiate and establish communication links between an RSU (Road-Side Unit) and an OBU (On-Board Unit) or between OBUs. The control channel is used by OBUs and RSUs to periodically broadcast announcements of available application services, warning messages and safety status messages. OBUs reply to broadcast messages using the service channel listed on the announcement since no replies are allowed to be transmitted on the control channel.

The presence of a high number of wireless nodes simultaneously transmitting over the control channel and the use of high broadcast transmission rates can provoke channel congestion resulting in the system's instability. Moreover, the future availability of a mix of priority and non-priority services sharing the same control channel will require the definition of mechanisms guaranteeing the latency and reliability of public safety communications. In this scenario, the successful implementation of inter-vehicle wireless communication systems for improving road safety will require careful and detailed investigations on its correct dimensioning under different operating conditions.

To date, several studies have analysed the performance of inter-vehicle wireless communication systems. For example, the work reported in [6] analysed the effect of realistic channel models on the throughput and latency of collision avoidance messages. To guarantee the reliability and latency of safety messages, [7] proposed different transmission policies. While providing valuable insights, these studies have not considered the dimensioning of inter-vehicle systems with regard to the driver's reaction time. Considering such timing is a crucial factor to guarantee that drivers will have sufficient time to react to a collision avoidance warning. Different traffic studies quantify the driver's reaction time around a mean of 1.5 seconds. Given the transmission power and range of WAVE systems, especially in shadowed urban environments, the driver's reaction time becomes a non-negligible dimensioning parameter. This observation is even more valid if we consider that the perception and braking time for the elderly with diminished visual, cognitive, and psycho-motor capabilities has been suggested to be equal to 3.5 seconds [8]. In this context, the aim of this work is to investigate the dimensioning of inter-vehicle wireless communication systems in realistic

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deployment scenarios considering various key operating parameters and the driver's reaction time. Based on the reported investigations, important conclusions regarding the system's dimensioning and the need to design schemes that guarantee the reliable and efficient delivery of vehicular safety applications will be extracted.

II. WAVE

The WAVE system evolves the 802.11a standard introducing new PHY and MAC techniques improving its operation in vehicular and safety applications, characterized by low latency requirements; according to [9], safety applications usually need to complete multiple data exchanges within 4 to 50ms. Like 802.11a, WAVE uses Orthogonal Frequency Division Multiplexing (OFDM), providing WAVE with data payload communication capabilities of 3, 4.5, 6, 9, 12, 18, 24, and 27 Mbps in 10 MHz channels. The standard uses 52 subcarriers that are modulated using binary or quadrature phase shift keying (BPSK/QPSK), 16-quadrature amplitude modulation (QAM), or 64-QAM. Forward error correction coding (convolutional coding) is used with coding rates of 1/2, 2/3, or 3/4. The rate-dependent parameters are summarised in Table I [5].

TABLE I. WAVE RATE–DEPENDENT PARAMETERS

Data Rate (Mbps) 802.11a	Data Rate (Mbps) WAVE	Modulation	Coding Rate
6	3	BPSK	1/2
9	4.5	BPSK	3/4
12	6	QPSK	1/2
18	9	QPSK	3/4
24	12	16-QAM	1/2
36	18	16-QAM	3/4
48	24	64-QAM	2/3
54	27	64-QAM	3/4

This work is focused on studying the dimensioning of traffic-safety related inter-vehicle wireless communications using the WAVE control channel. This channel transmits at a data rate of 6Mbps in a 10MHz channel, which corresponds to the QPSK transmission mode with a coding rate of ½. Figure 1 illustrates the physical level performance of this transmission mode for varying operating conditions [10]. The figure plots the PER (Packet Error Rate) as a function of the effective Signal to Interference and Noise Ratio (SINR), E_{av}/N_0, which represents the SINR reduced by a factor α to model the effect introduced by the cyclical prefix attached to each OFDM symbol.

In terms of the MAC layer, WAVE also reuses the IEEE 802.11.a access method based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). To alleviate the hidden terminal problem, WAVE also maintains the RTS/CTS (Request-To-Send/Clear-To-Send). However, it is important to note that the WAVE control channel operates in broadcast transmission mode, which results in the RTS/CTS being disabled. Consequently, all wireless nodes using the control channel are subject to the hidden terminal problem which increases the risk of channel congestion.

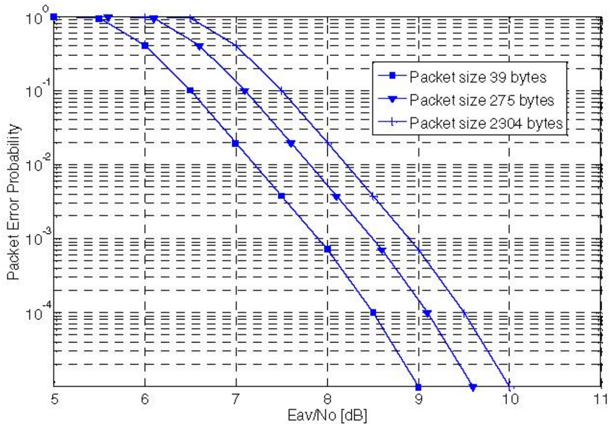

Figure 1. Packet Error Rate for the WAVE 6Mbps transmission mode (QPSK and ½ coding rate)

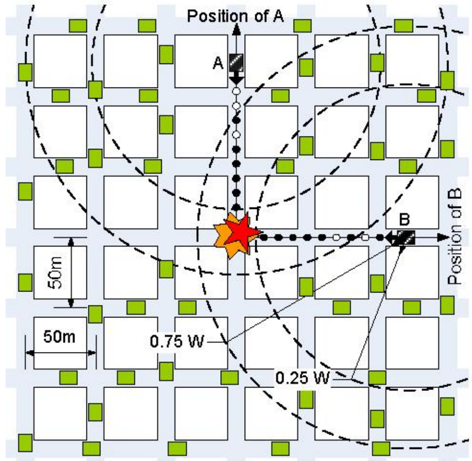

Figure 2. Collision avoidance in intersections

III. SIMULATION ENVIRONMENT

A. Scenario

To conduct this investigation, the ns2 simulator has been employed. ns2 is an open source discrete event simulator widely used in the wireless networking research community [11], especially for studying 802.11 systems. This work focuses on the critical intersection scenario illustrated in Figure 2. This scenario represents two vehicles moving towards an intersection with a risk of collision. To detect each other's presence, vehicles periodically broadcast basic safety messages on the control channel. To model the potential radio collisions that might occur in a traffic-dense environment, different vehicle traffic densities have been considered. The radio propagation effects have also been included by means of a log-distance pathloss and log-normal shadowing model. The probabilistic nature of the radio environment resulting from fading effects has been modelled through the PER performance shown in Figure 1. The effects of radio propagation on the reliability of safety messages can already be observed in Figure 2 where black and white circles represent, respectively, correctly and erroneously received broadcast messages. To analyse the trade-off between traffic density, reliability and time-bounded message transmissions, different transmitting powers and vehicular speeds have also been analysed. Table II summarises the main simulation parameters.

TABLE II. SIMULATION PARAMETERS

Parameter	Value
Speed [km/h]	40, 70, 100
Transmission power [W]	0.25, 0.75
Inter-vehicle spacing (IVS) [m]	40, 20, 13.3, 10
Emergency deceleration [m/s2]	8
Packet size [bytes]	100
Packet rate [pkts/sec]	10
Path-loss exponent	3.5
Shadowing std [dB]	4
Floor noise [dBm]	-95

B. *Traffic densites and maximum theoretical capacity*

The aim of this section is to estimate the traffic densities emulated using the parameters reported in Table II, and to show that such densities correspond to a wireless ad-hoc network load varying from low to high channel saturation. Considering a varying channel load is a key factor to validate any communication systems dimensioning investigation.

A vehicle's radio coverage area can be estimated using the log-distance pathloss model and radio propagation parameters reported in Table II. With transmission powers of 0.25W and 0.75W, wireless transmission ranges of 107m and 147m, respectively, can be obtained. Considering the Inter-Vehicle Spacing values reported in Table II, the traffic densities can then be easily estimated. The resulting number of vehicles within a node's transmission range is then shown in Table III for the emulated IVS values and transmitting powers.

TABLE III. NUMBER OF VEHICLES IN A WIRELESS'S NODE RANGE

IVS [m]	0.25W	0.75W
40	38	71
20	76	143
13.3	114	214
10	151	285

Table IV reports the 'ideal' theoretical capacity of the WAVE control channel for the emulation parameters reported in Table II. Such capacities have been obtained as follows. First, the time needed to transmit a message at the WAVE control channel transmission rate of 6Mbps is computed based on the message's size. It has then been assumed that no packet collision or radio propagation errors are experienced. Packets are also assumed to be perfectly time-aligned one after each other with a constant ideal separation of one Distributed Inter-Frame Space (64µs for WAVE) and an average backoff time[1] of $CW_{min}/2$ [5]. Table IV also reports the capacity estimation considering a backoff time equal to zero. Using the broadcast transmission rate, the 'ideal' theoretical capacity of a completely connected wireless ad-hoc network can finally be computed. Such 'ideal' capacity corresponds to the maximum number of nodes that could transmit over the control channel without packet collisions. Dimensioning the ad-hoc network over the estimated 'ideal' capacity cannot guarantee a packet-collision free transmission. Comparing the values reported in Table III and IV, it can be concluded that the emulated traffic densities allow for the WAVE control channel's performance to be analysed under low to high channel occupancy values.

[1] CW_{min} is the backoff or contention window considered for broadcast transmissions.

TABLE IV. IDEAL THEORETICAL WIRELESS AD-HOC NODE CAPACITY

Packet rate / payload	100 bytes (backoff $CW_{min}/2$)	100 bytes (backoff zero)
10 packets/sec	251	359

IV. EVALUATION RESULTS

Figure 3 shows the mean distance from the crashing point (position equal to 0 in the figure) at which vehicles receive the first broadcast message from the potentially colliding vehicle. The figure also shows the distance from the crashing point at which the driver reacts and he manages to stop the vehicle. As it can be observed, with low transmission powers and a high reaction time, the risk for collision is very high. This risk is reduced with the 1.5s driver's reaction time except for high speeds. In this case, the risk could be reduced by increasing the transmission power (see Figure 4), suggesting the need for adaptive power control schemes based on the vehicle's speed and position. Although the same observations are maintained when surrounding vehicles also transmit broadcast messages, direct comparison of Figure 4 and Figure 5 shows, that in this case, the system's performance decreases as the probability for packet collision increases (this effect is amplified in the case of high transmission powers since the vehicle's coverage range increases). To better illustrate the negative effect of an increasing vehicular traffic density on the potential of inter-vehicle wireless communications to prevent road accidents, Figure 6 shows, for varying IVS values, the distance from the crashing point at which the first broadcast safety message is received. The results illustrated in Figure 6 clearly show that as the vehicular traffic density increases, the driver has less time to react to a road danger alert.

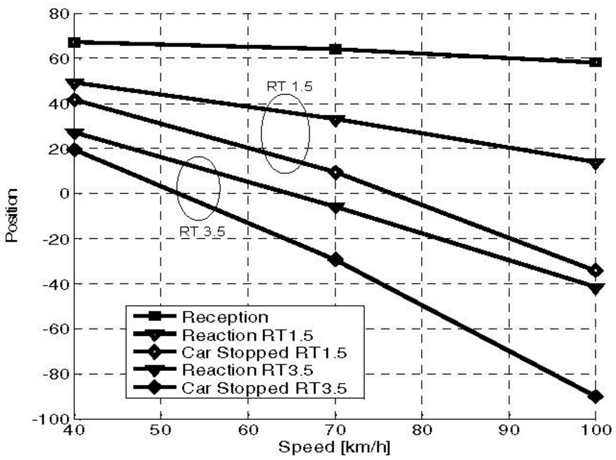

Figure 3. Position (TxPower=0.25W, no surrounding vehicles)

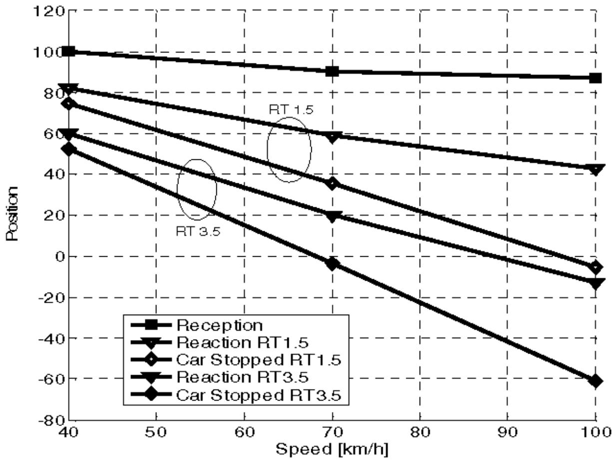

Figure 4. Position (TxPower=0.75W, no surrounding vehicles)

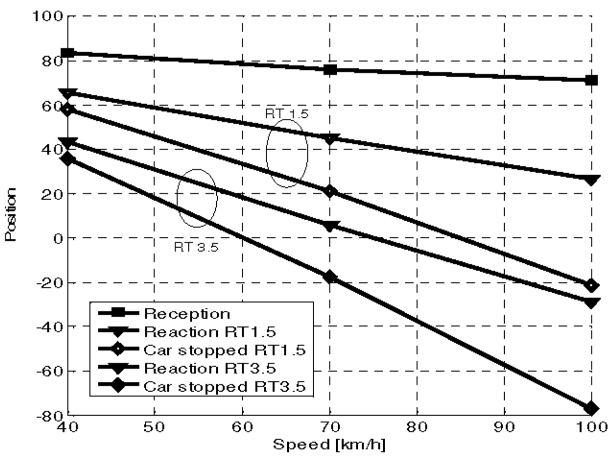

Figure 5. Position (TxPower=0.75W, IVS=40m)

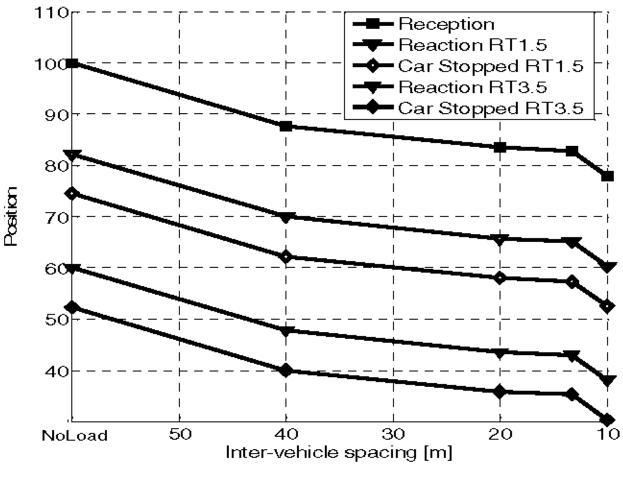

Figure 6. Position (TxPower=0.75W, speed=40km/h)

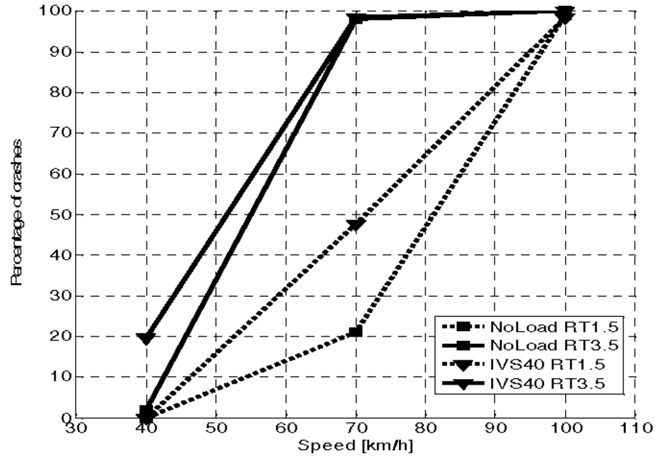

Figure 7. Percentage of crashes (TxPower=0.25W)

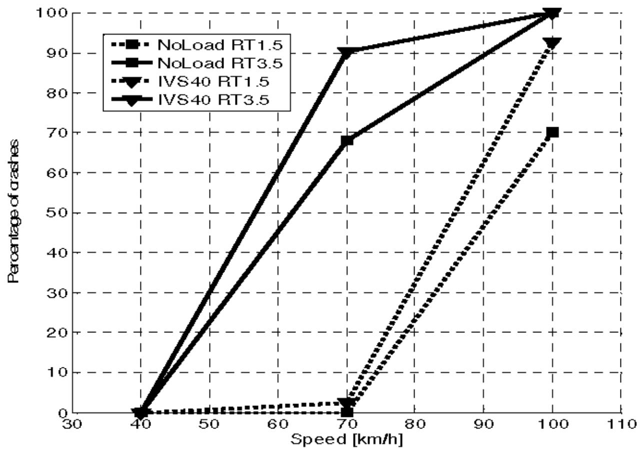

Figure 8. Percentage of crashes (TxPower=0.75W)

Figure 7 shows that considering a transmission power of 0.25W, a low percentage of crashes could only be guaranteed for vehicles moving at speeds below 40km/h. This percentage increases for 70km/h, especially when other surrounding vehicles also broadcast messages. Such percentages can be significantly reduced by increasing the transmission power (Figure 8). If vehicles move at very high speeds (i.e. 100km/h), considerably higher transmission powers should be considered in shadowed urban areas to successfully avoid collisions through inter-vehicle wireless communications. In fact, Figure 9 shows that at high speeds, a very limited number of safety messages are received before reaching the critical time compared to other vehicular speeds. The critical time corresponds to the shortest possible time at which a driver needs to receive a collision warning message considering its time to react (in this figure, 1.5s) and the time needed to decelerate.

Figure 10 shows the number of received safety messages for different instants before reaching the intersection; while the bars correspond to a single simulation example, the plotted curve represents the mean performance. The critical time has been computed considering a 1.5s driver's reaction time. This figure clearly demonstrates that the majority of messages are received once passed the critical time, i.e. when the driver would not be able to avoid the collision. Although such messages could be needed for further traffic dangers, they would also provoke message collisions to other surrounding vehicles. As a result, we propose as further research the implementation of opportunistic-driven transmission rate algorithms that increase the message transmission rate when approaching traffic dangers and reduce it when such dangers have been passed or when there is an important time before approaching them.

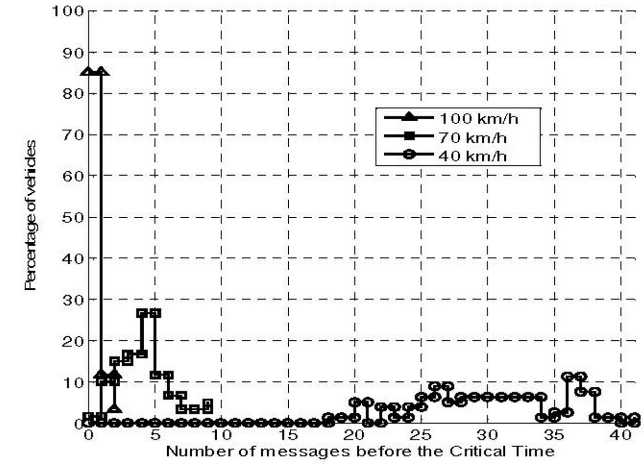

Figure 9. Percentage of vehicles receiving a given number of messages before the critical time (TxPower=0.75W and IVS=40m)

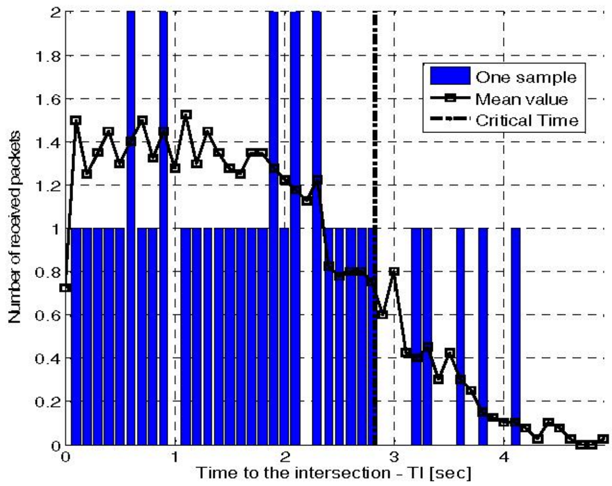

Figure 10. Number of received messages vs time to the intersection (TxPower=0.75W, speed=70km/h and IVS=20m)

V. CONSLUSIONS

This paper has investigated the performance of inter-vehicle wireless communication systems based on the forthcoming IEEE WAVE standard. In particular, the conducted investigations have focused on the system's dimensioning considering key operating parameters such as the vehicular speed, the wireless node's transmission power and vehicular traffic density. The obtained results show the important effect that these operating parameters have on the driver's capability to react to sudden road traffic alerts. Based on the observations reported in this work, the authors have highlighted the need to implement and optimize radio resource management techniques, such as adaptive power control and opportunistic-driven transmission rate, to guarantee the efficient and reliable transmission of broadcast vehicular safety messages.

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