Dissemination of Safety Messages in IEEE 802.11p/WAVE Vehicular Network: Analytical Study and Protocol Enhancements

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Abstract

Multi-channel IEEE WAVE 1609.4 protocol has been proposed to guarantee the co-existence of safety and non-safety applications over the same Vehicular Ad hoc NETwok (VANET) scenario. While the usage of multi-channel avoids the risk of collisions between applications allocated on different frequencies, its implementation on a single-radio transceiver poses some major concerns about the effective utilization of the channel resources. In this paper, we study the performance of safety applications over multi-channel single-radio VANETs, and we present three novel contributions in this regard. First, we propose an analytical analysis and a simulation study of IEEE 1609.4. We show the harmful impact of synchronous channel switching on the message delay and delivery ratio. Second, we investigate the problem of dissemination of safety broadcast messages over multi-channel VANETs, where the network is intermittently disconnected, due to the alternation of control and service intervals. Finally, we propose a WAVE-enhanced Safety message Delivery (WSD) scheme to enable fast dissemination of safety messages over multichannel VANETs, while guaranteeing compatibility with existing WAVE stack. To this aim, we formulate the dissemination problem as a multi-channel scheduling problem. We further introduce cooperation among vehicles to reduce the dissemination latency. Simulation study shows the ability of the WSD scheme to enhance the performance of IEEE 1609.4 in terms of message delay and delivery ratio under different topologies and various applications.

Keywords: VANETs, IEEE WAVE 1609.4, Multi-channel technology, Performance Evaluation.

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1. Introduction

In the last years, the potentials of Vehicular Ad Hoc NETworks (VANETs) as technological enablers of a wide range of novel applications based on inter-vehicular communication have attracted considerable attention from both academia and industries. Most of these applications are focused on safety issues, in order to reduce the risk of casualties on the roads [3] and to assist the drivers' with real-time information about road and traffic conditions [14]. However, we also notice an increasing interest towards applications related to enhanced drivers' comfort and entertainment, and towards urban sensing scenarios [28], based on "social" and collaborative behaviors among users. How to guarantee the coexistence of safety and non-safety vehicular applications operating over the same scenario constitutes an important issue, that has been recently addressed by spectrum regulation agencies and by international standardization committees. On the one hand, a specific portion of the spectrum has been reserved for Dedicated Short-Range Communication (DSRC) among vehicles in both the US and Europe. The DSRC band is divided into 7 channels, classified into 1 common control channel (CCH) for safety-related information, and 6 service channels (SCH) for generic non-safety applications. On the other hand, the IEEE P1609 Working Group in charge of the standardization of the Wireless Access in Vehicular Environment (WAVE) stack has released several protocols that take into account the co-existence problem of vehicular applications with different classes and QoS requirements. At the MAC Layer, service differentiation among Traffic Classes (TCs) is achieved through the utilization of the Enhanced Differentiated Channel Access (EDCA) functionalities [42] inherited from the IEEE 802.11e protocol. At the upper MAC layer, the WAVE 1609.4 protocol [23] has been proposed to enable multi-channel operations on the DSRC band with single-radio transceivers. Based on this scheme, each vehicle periodically switches between the Control CHannel Interval (CCH) and Service CHannel Interval (SCH). During CCH intervals, each vehicle is tuned to the DSRC control channel and exchanges data of safety-related applications. During SCH intervals, vehicles might be tuned to any of the 6 service channels, and exchange infotainment information. A clear advantage of the time and frequency diversity introduced by the WAVE 1609.4 protocol is the co-existence of different TCs that might operate on the same scenario without experiencing mutual interferences. However, several recent studies revealed that halving the available bandwidth might seriously compromise the performance of safety and non-safety vehicular applications over realistic scenarios [9, 10, 7, 25, 31]. In this paper, we focus on safety-related applications, since they are recognized to have more stringent QoS requirements in terms of delivery delay and ratio, and we attempt to answer the following key questions: how is the 1609.4 environment affecting the performance of event-driven safety-applications? and more generally: how can we guarantee fast and efficient dissemination of safety-related messages on multi-channel VANET environments?

In order to address these key questions, we propose a threefold contribution on the study and evaluation of multi-channel VANETs in this paper. First, we analyze through analytical models and simulation results the performance of safety-related applications on 1609.4 multi-channel VANETs, and we demonstrate that on single-radio configurations the synchronous channel switching operations enforced by the WAVE 1609.4 protocol might have a harmful impact on the delivery delay and ratio of safety-related broadcast applications. Second, we study the problem of minimizing the delivery delay of broadcast communication on single-radio multi-channel environments, where the network might be fragmented into multiple cliques of connectivity on different channels. Finally, we propose a WAVE-enhanced Safety message Delivery scheme (WSD) that is designed to enable fast dissemination of safety messages over multichannel VANETs. The proposed scheme works by enabling the dissemination of safety messages during SCH intervals, and can benefit form cooperative channel scheduling approach to guarantee the dissemination of the message over all the service channels. Simulation results confirm the effectiveness of the WSD scheme in greatly reducing the average delivery delay when compared to the legacy WAVE 1609.4 standard over realistic multi-lane VANET topologies.

The rest of the paper is organized as follows. In Section 2.1, we provide a brief description of the WAVE stack while focusing on the WAVE 1609.4 standard. We review in Section 2.2 the existing enhancements proposed in the literature. In Section 3, we introduce the system model used in this paper. In Section 4, we propose an analytical study (validated through simulations) of the performance of safety-related applications over multi-channel VANETs. Based on this result, we introduce in Section 5 the WSD scheme, and address the channel scheduling problem. Section 6 extends WSD in the presence of cooperative nodes and describes the heuristic used to solve the multi-machine scheduling problem. Section 7 evaluates the performance of the WSD and the legacy WAVE 1609.4 protocols using the Ns-2 extension for multi-channel VANETs [18]. Section 8 concludes the paper and discusses future extensions.

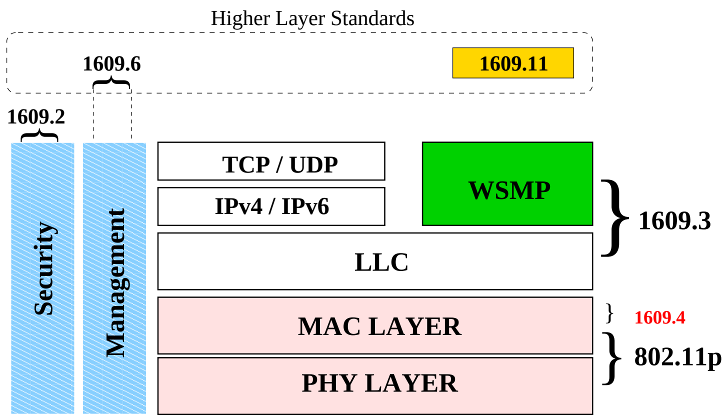


Figure 1: The WAVE stack architecture [11].

2. Related Works

2.1. The IEEE 802.11p/WAVE standards

The IEEE Working Groups are actively working on the development of the Wireless Access in Vehicular Environments (WAVE) family of standards. WAVE provides automobile manufactures with a complete and coherent ground for wireless vehicular communication that copes with the problems incurred by car mobility. Several IEEE trial-use standards have been published in 2006-2007, including 1609.1 (remote management services), 1609.2 (security services), 1609.3 (networking services) and 1609.4 (multi-channel operation). These standards were used to support a series of field trials. With the lessons learned from the field trials, “full use” standards are being published to replace the trial-use ones. New versions of 1609.3 and 1609.4 were published in 2010, along with two new standards 1609.11 (electronic fee collection) and 1609.12 (provider service identifier allocations). Two new standards are now in progress which are 1609.0 (architecture) and 1609.6 (remote management). On the other hand 1609.1 did not get enough support in the trials, and it was no more maintained. Medium Access Control (MAC) and PHYsical (PHY) operations on a single logical channel are regulated by the IEEE 802.11p WAVE standard, which is mainly based on previous IEEE 802.11 standards. The PHY layer is derived from the IEEE 802.11a protocol, while the MAC layer implements the Enhanced Distributed Channel Access (EDCA) mechanism originally provided by the IEEE 802.11e scheme. In this paper, we are mainly interested in the IEEE 1609.4 standard. Figure 1 shows the WAVE stack architecture.

At the early stages of the VANET deployment, cars are expected to be equipped with a single radio device. Multiple radios technology still suffers from technical problems and will incur additional costs for manufacturers. The IEEE 1609.4 Multi-Channel Operation Standard [23] has been proposed in 2010 (as a revision of the previous IEEE 1609.4-2006 standard) to enhance the underlying IEEE 802.11p [42] MAC protocol with multi-channel operations over a single-radio transceiver. The IEEE 1609.4 employs both time and frequency division access schemes. The channels used by the IEEE 1609.4 standard are allocated in the DSRC band which has been reserved for vehicular communications in both the US and Europe. Seven 10 MHz channels are available, divided into one control channel and six service channels. Figure 2 shows the current frequencies used in the US, where the DSRC band is also known as Intelligent Transportation Systems (ITS) Radio. It is assumed that all vehicles maintain strict synchronization with the Coordinated Universal Time (UTC) that can be acquired from Global Positioning System (GPS) devices or from other vehicles. Based on this time information, vehicles continuously alternate between the following two time intervals:

- *Control CHannel Interval (CCHI)*: during CCHI, all vehicles should be tuned to the Control CHannel (CCH, also known as channel 178) and exchange safety information. The WAVE Short Message Protocol (WSMP) is the only acceptable message exchange protocol at the CCH. WSMP is designed to deliver low latency in fast varying environments [24]. Usage of the CCH has been limited to safety messages exchange and WAVE Service Advertisements (WSA) to minimize traffic at that channel. WSA are exchanged to publicize services to be offered during the next interval.

- *Service CHannel Interval (SCHI)*: during SCHI, vehicles can switch to a Service CHannel (SCH) to be involved in a service of interest. Needed information about offered services can be fetched from WSA where a Provider Service Identifier (PSID) octet string is used to identify a specific service. PSIDs are being allocated and recorded in the IEEE 1609.12 draft standard [12].

To summarize, all devices are required to monitor the control channel during CCH intervals. The SYNChronization (SYNC) interval is the summation of the CCH interval and SCH interval. The SYNC Interval is 100 ms in length and equally divided between control and service channel intervals (in the default values) [23]. Guard intervals are introduced at the start of each interval to minimize the effect of timing inaccuracies and Radio Frequency (RF) switching de-

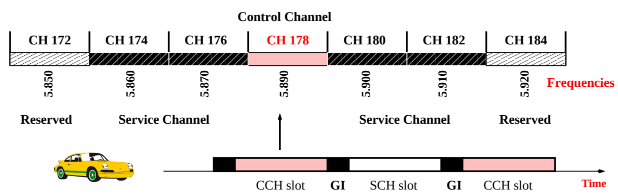


Figure 2: The DSRC spectrum frequencies and the IEEE 1609.4 WAVE protocol operations.

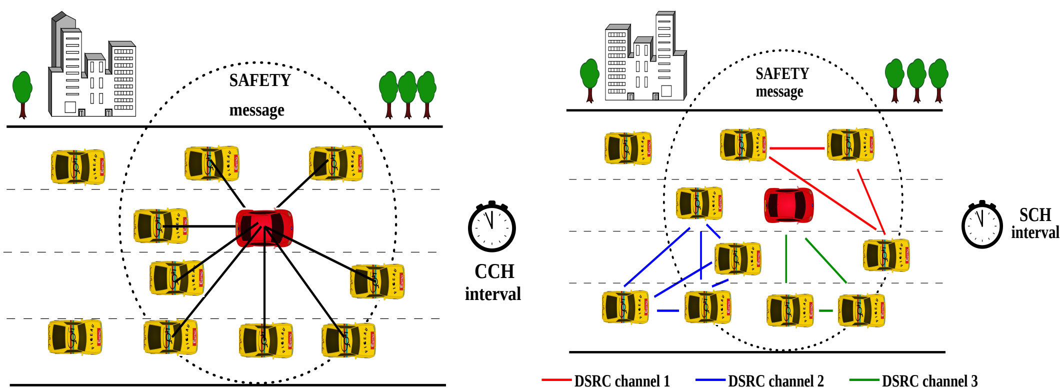
lays. Typical values for the Guard interval ranges from 4 to 6 ms [25]. During the Guard interval, all ongoing transmissions are aborted and the MAC layer is flagged as busy. At the beginning of each interval, previous MAC activities are suspended and the corresponding ones are started or resumed, thus ensuring that each packet is transmitted on the correct channel. For instance, a vehicle interested in an audio file transfer service will switch to the corresponding service channel to start receiving the file. If the transfer takes too long to complete, the vehicle must switch to the control channel to receive safety messages and then switch back to the service channel to resume the file transfer. Thus, using the multi-channel coordination, a vehicle can periodically monitor the control channel for safety messages while it continues to use available infotainments services in the network.

2.2. Multi-channel VANETs and IEEE 1609.4 protocol's enhancements

Performance evaluation of multi-channel VANETs based on the WAVE 1609.4 protocol has been the subject of several recent works. Most of these studies focused on analyzing the impact of channel switching operations on the QoS requirements of vehicular applications, assuming single-radio VANETs. Among other works, we cite the analytical model of the IEEE MAC 802.11p presented in [31] and the simulation studies in [25][18][9][10][13], where the authors demonstrate that the CCH/SCH switching operations might cause synchronization of the backoff process at the MAC layer, which increases the probability of frame collisions for beacon messages transmitted on the control channels. From these studies, it emerges that the main issue of multi-channel VANETs is how to guarantee the co-existence of safety and non-safety applications, while providing efficient utilization of the channel resources. To this aim, several enhancements of the WAVE protocol stack have been proposed, based on three different approaches: (*i*) time-scale optimizations, (*ii*) frequency-scale optimizations, and (*iii*) MAC-related optimizations. As an example of the first approach, the authors of [40] propose to dynamically adjust the length of the CCH/SCH interval based on the traffic loads of each channel. In frequency-scale optimizations, dynamic spectrum management techniques are used to solve the problem of congestion on service/control channels, that might originate due to the limited bandwidth of DSRC channels (10 Mhz). For this, the Cognitive Radio (CR) and Dynamic Spectrum Access (DSA) solutions [8] were found to be suitable approaches to increase the DSRC bandwidth for safety-applications, by using vacant frequencies in the DTV band [16][17]. Finally, works that followed the third approach investigated how to enhance the performance of multi-channel VANETs by optimizing the transmission operations at the MAC layer, but without affecting the multi-channel operations enforced by the WAVE 1609.4 protocol. For instance, the authors of [25] suggest to schedule the generation of beacon messages only during the CCH interval, in order to avoid the problem of synchronous collisions at the start of the CCH interval. Techniques to randomize the transmission of the beacons during the CCH are proposed in [7][35]. An adaptive MAC contention control scheme is described in [9], where the authors propose to dynamically adapt the MAC Contention Window (CW) size based on the estimated contention conditions of the CCH channel. To the best of our knowledge, few works discuss the impact of the CCH/SCH switching on the performance of safety applications, which constitutes the main focus of our paper. The only works that addresses a similar problem are [30][35]. However, we remark here the distinctive and original characteristics of our approach: (*i*) we provide solutions to minimize the delivery delay of safety messages on the 802.11p/WAVE multi-channel MAC, (*ii*) we do not assume any specific scheduling from the application, and (*iii*) we do not require any changes to the existing IEEE WAVE standards.

3. System Model

In this paper, we consider a multi-lane vehicular environment as the one depicted in Figures 3(a) and 3(b). We assume that each vehicle of the scenario is equipped with an IEEE 802.11p compliant radio device, and implements the WAVE 1609.4 protocol for multi-channel operations as described in Section 2.1. During the CCH interval, vehicles are tuned to the control channel, so that each vehicle is connected to all nodes in its transmitting range (Figure 3(a)). During the SCH interval, vehicles can be tuned to seven different DSRC channels, and as a result, the network graph might be fragmented in up to seven different cliques (as shown in Figure 3(b)). In our study, we do not assume any specific channel allocations during the SCH interval, i.e., each vehicle can randomly decide to tune its radio to any of the service channels, or remain tuned to the control channel.



(a) (b)

Figure 3: The vehicular connectivity at different time intervals foreseen by the WAVE 1609.4 standard: during the CCH interval (Figure 3(a)) and during the SCH interval (Figure 3(b)).

Based on the current state-of art of vehicular applications, safety messages can be divided into two categories: event-driven emergency messages and routine status HELLO messages [41]. Event-driven emergency messages are triggered by a sudden change in the vehicular environment during either CCH or SCH intervals. On the other hand, routine status HELLO messages are periodically exchanged during control channel interval, and are used to inform neighbors about the current status of the originating node (e.g., location, speed and direction) [21]. To enable a DSRC system to provide safety at the road level, it is essential to ensure that both categories of safety messages are received by neighbor vehicles in a timely fashion. In this paper, we limit our research scope to high priority event-driven safety messages (denoted as α in the following) which are considered to directly affect human lives. To this aim, we impose that each α message generated by a vehicle η must be successfully delivered to all its neighbors. Although each neighbor might in turn re-broadcast the safety message (thus enabling multi-hop dissemination), we focus our work on single-hop dissemination, and more specifically on the problem of minimizing the delay overhead introduced by the WAVE 1609.4 protocol on multi-channel single-radio vehicular environments. This delay might severely affect the performance of safety-related applications, as demonstrated in the following section.

4. Motivations

In this section, we investigate the performance of broadcast applications over multi-channel VANETs through analytical and simulation results, and we show that synchronous channel switching operations enforced by the IEEE 1609.4 protocol might considerably affect the message delay and delivery ratio of safety-related applications. These results raise concerns about WAVE capability of providing safety at the road level, and thus justify the need of protocol enhancements that take into account the QoS requirements of vehicular applications.

Generally speaking, a event-driven safety message α can be generated at the application layer any time during a SCH or CCH interval. In the following, we refer to the scenarios where α is generated during a SCH and CCH interval as *Mode I* and *Mode II*, respectively.

Mode I scenario. If generated during the SCH interval, the α message will not be immediately transmitted, but rather, it will be queued till the next CCH interval. As a result, the α message will experience an additional queuing delay before being transmitted. Moreover, MAC collisions might occur at the start of the next CCH interval as a consequence of the synchronization of backoff processes, as discussed also in [9]. In the following, we derive an upper bound on the message delay and delivery ratio of safety-related applications operating in *Mode I*, and then validate the correctness of the analytical results using simulation tool. We consider the system model described in Section 3, and we add the following assumptions to make the analysis tractable: (*i*) each vehicle generates exactly 1 safety-related message during the SCH interval, (*ii*) all messages have the same payload size S, and (*iii*) all vehicles are in the same transmission area, and the set of one-hop neighbors remains the same during one SYNC interval (i.e. the number of vehicles is constant during a SYNC interval). Under these assumptions, the average message delay required to transmit α can be expressed as the sum of the average queuing delay ($E[q]$), the average contention delay ($E[c]$) on the control channel, the average transmission delay ($E[t]$), and the average propagation delay $E[p]$. If we assume the propagation delay to be negligible (i.e. $E[p] = 0$), then we can express the average message delay $E[d]$ as follows:

$$E[d] = E[q] + E[c] + E[t] \tag{1}$$

Since we assume that each α message is generated during the SCH slot and then transmitted during the CCH slot, then $E[q]$ can be computed as:

$$E[q] = \frac{SCH_d}{2} + GI_d \tag{2}$$

where SCH_d and GI_d are the length of the SCH and the Guard Intervals (in seconds) respectively. If we let τ be the probability to transmit in a given slot, and if we assume a uniform probability distribution to select a slot within the current Contention Window (CW), then τ can be derived as in [4][6]:

$$\tau = \frac{1}{E[CW]+1} = \frac{2}{CW_{min}+1} \tag{3}$$

Since the transmission happens in broadcast, exponential backoff and MAC acknowledgments are disabled, and message are transmitted without re-transmission by using the minimum size of the CW, i.e. CW_{min}. If we let p_{idle} be the probability that a channel is idle in a given slot, and p_{busy} its converse, $p_{success}$ be the probability that a slot is occupied by a successful transmission and p_{coll} the probability that a collision occurs during a slot, and finally assume a scenario with N nodes, it is easy then to verify that p_{idle}, p_{busy}, $p_{success}$ and p_{coll} can be computed as follows:

$$p_{idle} = (1-\tau)^N \tag{4}$$

$$p_{busy} = 1 - p_{idle} \tag{5}$$

$$p_{success} = N \cdot \tau \cdot (1-\tau)^{N-1} \tag{6}$$

$$p_{coll} = 1 - p_{idle} - p_{success} \tag{7}$$

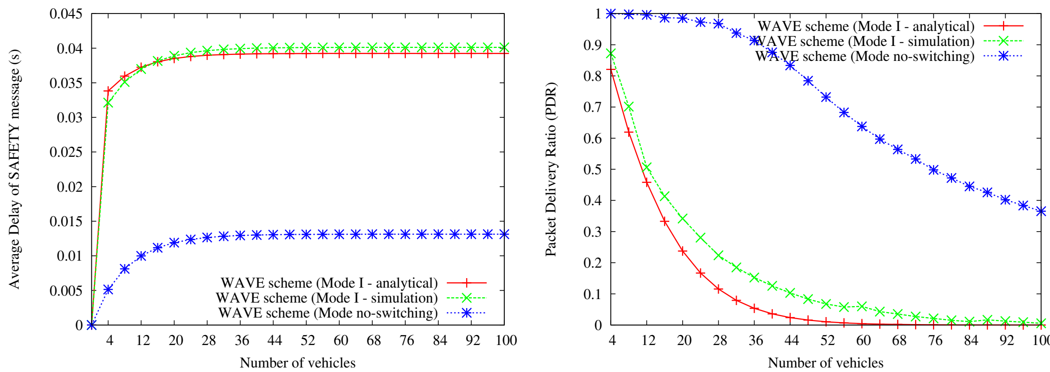
The average contention delay $E[c]$ can be expressed as a function of the average CW size $E[CW]$ and the average duration of each logical slot T_{slot}:

$$E[c] = E[CW] \cdot T_{slot} = \frac{CW_{min}-1}{2} \cdot T_{slot} \tag{8}$$

The average duration of the logical slot T_{slot} can be derived, as proposed in [4]:

$$T_{slot} = (1-p_{busy}) \cdot \sigma + T_{success} \cdot p_{success} + T_{coll} \cdot p_{coll} \tag{9}$$

where σ is the duration of an empty slot according to the MAC 802.11p [42]. $T_{success}$ is the time required for a successful transmission and T_{coll} is the average



(a) (b)

Figure 4: Mode I analysis: the average delay for the single-channel and multi-channel WAVE schemes is shown in Figure 4(a)). The Packet Delivery Ratio (PDR) comparison is shown in Figure 4(b).

time of a collision event. Based on the transmission delay of a message $E[t]$, the exact value of $T_{success}$ and T_{coll} can be derived as:

$$T_{success} = DIFS + \sigma + E[t] \quad (10)$$

$$T_{coll} = EIFS + \sigma + E[t] \quad (11)$$

Finally, $E[t]$ can be expressed as the time required to transmit an α message of size S with data-rate R, and including the transmission time of the preamble (T_{PRE}):

$$E[t] = \frac{S}{R} + T_{PRE} \quad (12)$$

In a similar way, we can derive the Packet Delivery Ratio (PDR) metric in the *Mode I* scenario described earlier. Assuming that all vehicles are in the same interference range and each vehicle will generate only one broadcast message at the start of the interval, PDR can be expressed as the probability of having a successful transmission, knowing that the slot is busy, i.e.:

$$PDR = P(successful|busy) = \frac{p_{success}}{p_{busy}} = \frac{N \cdot \tau \cdot (1-\tau)^{N-1}}{1 - ((1-\tau)^N)} \quad (13)$$

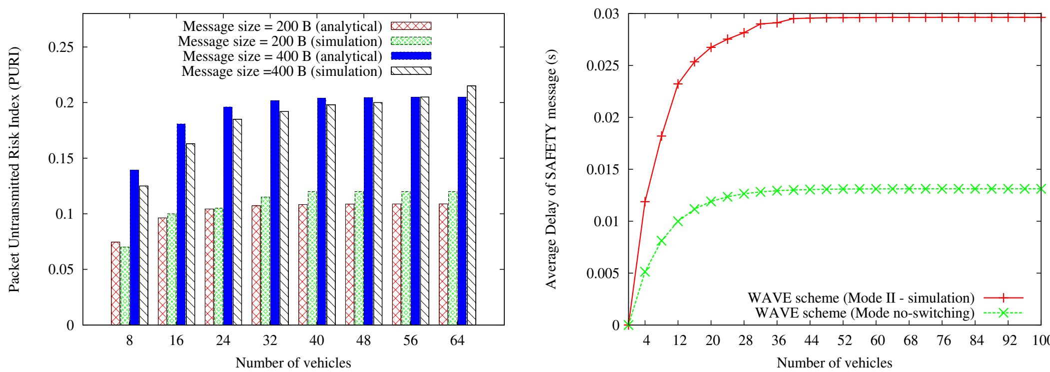
In Figure 4(a), we depict the average delay experienced by the α message generated in *Mode I*, as a function of the number of vehicles (payload size of α messages is set to 200 bytes in this experiment). In the same figure, we depict the analytical delay[2] (computed through Equation 1) and the simulation results[3], obtained through the Ns-2 model of the 1609.4 protocol described in [18]. Results in Figures 4(a) and 4(b) are averaged over 500 different runs. It is easy to notice that analytical delay closely follows the simulation delay, thus confirming the correctness of the analytical model described above. Moreover, to underline the impact of periodic channel switching imposed by the IEEE 1609.4 protocol, we simulate a scenario with single-channel Mode[4], according to which all vehicles are always tuned to CCH, and no channel switching occurs. Figure 4(a) confirms that multi-channel WAVE scheme experiences significant extra-delay as a consequence of halving the available bandwidth. Un-transmitted packets are queued during all the SCH interval before performing any transmission attempt on the control channel. Figure 4(b) depicts the PDR metric for the *Mode I* scenario. Results in Figure 4(b) validate the correctness of Equation 13, and demonstrates that the WAVE multi-channel scheme suffers from high packet drops. In *Mode I*, all vehicles will start contending for the channel only at the start of the CCH interval to transmit the α message while in *Mode no-switching*, vehicles are offered double this capacity. In this regard, techniques to mitigate the problem of channel contention in IEEE 1609.4 networks are proposed in [9].

Mode II scenario. If generated during a CCH interval, the α message will be broadcasted on the control channel. However, we might run into a situation where α does not gain access to the medium and is not broadcasted during the CCH interval due to specific channel conditions (such as high contention at the control channel, or the CCH interval expiring shortly after α is generated). In that case, α must be queued till the next CCH interval, and will witness an additional delay before being transmitted. To study the frequency of packet un-transmitted events and analyze their impacts on the system performance, we introduce the notion of Packet Un-transmitted Risk Index (PURI), defined as the probability that an α message generated randomly during a CCH interval will not get access to the medium by the end of that same CCH interval. Again, we assume that each vehicle will generate only one α packet to be transmitted during the CCH interval. We can then approximate the PURI as the probability that the α message will be generated at an instant of time t greater than $CCH_d - E[d]$, where CCH_d is the

[2]denoted as WAVE scheme (Mode I - analytical)

[3]denoted as WAVE scheme (Mode I - simulation)

[4]denoted as WAVE scheme (Mode no-switching)



(a) (b)

Figure 5: Mode II analysis: the PURI metric is shown in Figure 5(a)). The average delay of the single-channel and multi-channel WAVE schemes is shown in Figure 5(b).

duration of the CCH interval and $E[d]$ is the upper bound on the average delay given by Equation 1 (worst case analysis):

$$E[PURI] = P(t > (CCH_d - E[d])) = \frac{CCH_d - E[d]}{CCH_d} \tag{14}$$

Figure 5(a) shows the PURI as a function of the number of vehicles and for different payload sizes of the message. For the simulation results, we average the results of 400 different runs, where we randomly choose the time in which α is generated during the CCH interval. It is easy to see that PURI increases when more traffic is introduced in the channel due to the increase in the contention level. Similarly, Figure 5(b) depicts the average delay for the *Mode II* scenario, for the WAVE single-channel, and WAVE multi-channel configurations. Figure 5(b) confirms that the multi-channel WAVE scheme experiences significant extra-delay as a consequence of the un-transmitted packets that are queued during the SCH interval before performing a new transmission attempt on the control channel.

From the above analysis, we conclude that to allow drivers to react appropriately to emerging critical situations, it is fundamental to minimize the additional delay posed by the WAVE multi-channel environment. In this paper, we attempt to achieve this goal by allowing the transmission of the α message during SCH intervals. The main challenge in this approach is that vehicles can be tuned to seven DSRC different channels during SCH intervals. However, this challenge can be overcome by leveraging vehicles cooperation to relay a copy of α on each channel, and by carefully deciding the channel scheduling to use. For this aim, we introduce the WAVE-enhanced Safety message Delivery (WSD) scheme described next in Section 5.

5. WAVE-enhanced Safety Message Delivery (WSD) scheme

In this Section, we propose an algorithmic formulation for the problem of dissemination of event-driven high priority safety messages during SCH intervals. In the next subsections, we first present a problem formulation and introduce some notations. Then, in the next subsection, we discuss the details of our proposed algorithm called `WAVE-enhanced Safety message Delivery scheme` (WSD). In the last subsection, we introduce the idea of cooperation that can be used to improve the dissemination algorithm. Finally, to provide a better reading experience, Table 1 reports a list of acronyms and symbols used in Sections 5 and 6.

5.1. Formulation and Notations

A vehicle willing to transmit a high priority safety message during a service channel interval has the following two objectives: (*i*) reach all its one-hop neighbors while (*ii*) minimizing the average delivery delay to reach a neighbor, $E[d_n]$. The vehicle is subject to the constraint to reach all its neighbors before the expiration of the SCH interval.

First, let us denote by $\mathbf{U}$ the list of DSRC channels c_i (with $0 \leq i \leq 6$) where the middle channel c_3 is the control channel (also referred to as channel 178). $\mathbf{U}$ is the universe under consideration in this study. We associate with each channel c_i two cost metrics at each service channel interval: (*i*) T_i, the channel access delay during SCH interval and (*ii*) M_i, the number of nodes available at c_i during that same SCH interval. Moreover, T_i has two components: the Radio Frequency (RF) switching delay denoted as d_{RF} and the average message delay $E[d]$ discussed in Equation 1 in Section 4. We assume the value of T_i to be known by each node.

Also, we denote by η the node (vehicle) generating one event-driven safety message α, and associate with η a set of one-hop neighbors denoted by $\mathbf{N}$. We assume that the set of one-hop neighbors remains the same during one SYNC interval (equivalent to duration of 100ms). Moreover, each neighbor of η will be available at a specific channel c_i during the next SCH interval. We assume that all nodes exchange their next service channel and their one-hop neighbors set through `HELLO` messages broadcast during CCH intervals. The exchange of next service channel and one-hop neighbors set induce additional traffic overhead

Table 1: Abbreviations and Notations

SCH	service channel
CCH	control channel
SCHI	service channel interval
CCHI	control channel interval
GI	guard interval
SYNC	synchronization interval
WSA	WAVE Service Advertisement
α	high priority safety message
η	vehicle generating α
c_i	channel i
$\mathbf{U}$	list of all DSRC channels c_i
T_i	access delay of channel c_i
M_i	number of nodes available at c_i
$\mathbf{N}$	one-hop neighbors of η
$\mathbf{L}$	to-be-covered channels set
$\mathbf{N^i}$	set of neighbors of η tuned at c_i
$E[d_n]$	average delivery delay to reach a neighbor
$\mathbf{G}$	set of cooperating nodes (including η itself)
J_j	job j
p_j	processing time of job J_j
d_j	deadline of job J_j
w_j	weight coefficient of job J_j
C_j	completion time of job J_j
M_m	machine m
P	identical parallel machines
$\mathbf{M_j}$	set of machines capable of processing job J_j
$\mathbf{E}_m$	set of eligible jobs to be scheduled on machine M_m
W_m	potential workload: cardinality of the set $\mathbf{E}_m$

in the network. HELLO messages size can exceed 500 bytes with the security overhead foresee in [33]. We require only 3 additional bits to exchange the next service channel. The size of the one-hop neighbors set varies from sparse rural scenarios to congested highway scenarios. We consider an average 2-lanes scenario where following distance between vehicles is 20 meters. With a transmission range of 300 meters, each vehicle has an average of 30 neighbors. Thus, maximum overhead in the depicted scenario does not exceed 30 bytes or 6% of the HELLO message size. It is worthy to mention that the real overhead value dynamically changes with the traffic density. Moreover, we will show in the subsequent sections that this overhead is justified by the improvement achieved in the terms of reduced safety message delivery delay.

Hence, η has full knowledge of its one-hop and two-hop neighbors. Moreover, using collected next service channel entries, η builds the to-be-covered channels set denoted as $\mathbf{L}$, with $\mathbf{L} \subseteq \mathbf{U}$. $\mathbf{L}$ includes the channels c_i where η one-hop neighbors will be available during the next SCH interval. The message α has to be broadcasted in all the channels in the set $\mathbf{L}$. Furthermore, η decomposes its one-hop neighbors set $\mathbf{N}$ into i different subsets $\mathbf{N^i}$. For each channel c_i, we associate the set $\mathbf{N^i}$ defined as the set of one-hop neighbors of η that will be tuned at channel c_i during the next SCH interval. Finally, $E[d_n]$ is defined as the completion time (delay) to cover all channels in $\mathbf{L}$ weighted by the number of neighbors M_i at each channel, i.e.:

$$E[d_n] = \frac{1}{N} \sum_{i \in \mathbf{L}} C_i \cdot M_i \tag{15}$$

Completion time C_i is defined as the time elapsed until channel c_i is covered. Completion time will be further discussed in Section 6.1. Note that vehicles decide on their next service channel based on WAVE Services Advertisements (WSA) received during the CCH interval. Exchanging the next service channel and one-hop neighbors set might raise some privacy concerns that need to be answered. However, we consider these issues to be outside the scope of this paper and we refer interested readers to the following literature addressing privacy in VANETs [5] [15].

Given a vehicle η *and its neighbors* $\mathbf{N}$ *Given remaining time till the end of SCH interval* *Find a schedule to broadcast message* α *over channels* $\mathbf{L}$ *That minimizes average delivery delay* $E[d_n]$

Finally, The optimization problem discussed so far is summarized in the box above. Also, a mathematical formulation is presented based on the time-indexed formulation presented in [36] [39] where time is divided into periods. Period t starts at time $t-1$ and ends at time t. The planning horizon is denoted by T, which means that all channels have to be covered by time T that represents the remaining time till the end of the current SCH interval:

$$\min \sum_{i \in \mathbf{L}} \sum_{t=1}^{T-T_i+1} C_i \cdot M_i \cdot x_{it}$$

subject to

$$\sum_{t=1}^{T-T_i+1} x_{it} = 1 \qquad (i \in \mathbf{L}),$$

$$\sum_{i \in \mathbf{L}} \sum_{s=t-T_i+1}^{t} x_{is} \leq 1 \qquad (t = 1, ..., T),$$

$$\sum_{i \in \mathbf{L}} T_i \leq T,$$

$$x_{it} \in \{0, 1\} \qquad (i \in \mathbf{L}; t = 1, ..., T - T_i + 1),$$

where $x_{it} = 1$ if channel c_i is covered at period t and 0 otherwise. The first constraint ensures that each channel is covered exactly once while the second constraint states that one channel can be covered at most during any time period. The third constraint ensures that all channels are covered by the end of the SCH interval.

5.2. WSD Proposed Algorithm

The `WAVE-enhanced Safety message Delivery` (WSD) algorithm aims to broadcast the event-driven high priority safety message α at all channels c_i belonging to $\mathbf{L}$ while minimizing the average delivery delay to reach a neighbor. The WSD algorithm can be described as follows:

At each CCH interval, vehicles collect `HELLO` messages from neighbor nodes and construct the following sets: $\mathbf{N}$, $\mathbf{L}$, and all the sets $\mathbf{N^i}$. These sets have small cardinalities and thus do not impose memory overhead. We refer to this routine as `Data Collection` routine.

During each SCH interval, if a safety message α is available for transmission, then node η computes the optimal schedule for disseminating α as follows:

1. If the set **L** is not empty, sort its elements in increasing order of $\frac{T_i}{M_i}$.
2. Tune to the channel with the smallest $\frac{T_i}{M_i}$, transmit α and remove this channel from the set **L**.
3. Repeat this step until **L** becomes empty.

This problem is known as the weighted shortest processing time rule in the area of machine scheduling. It is also known as Smith's ratio rule. Smith had shown in [34] that weighted shortest processing time rule provides optimal solution for total weighted completion time.

If the SCH interval expires and **L** is not empty yet, then vehicle η decides to re-broadcast α at the next CCH interval to ensure its reception by all neighbors. This step ensures message dissemination to all neighbors. The overall `WSD` algorithm is described in Algorithm 1.

Algorithm 1: WAVE-enhanced Safety message Delivery scheme (WSD)

---

1. At each CCH interval, use `HELLO` messages to run `Data Collection` routine.
2. During each SCH Interval, upon receiving an α message:
repeat
  2.a Schedule the channel from the set **L** with the smallest fraction $\frac{T_i}{M_i}$.
  2.b Remove the scheduled channel from **L**.
until $\mathbf{L} = \emptyset$
3. At the end of the SCH Interval:

if ($\mathbf{L} = \emptyset$) **then**
  Terminate
else
  η re-broadcasts a copy of α at the start of the next CCH interval.
end if

5.3. Enhancing WSD with vehicles' cooperation

The `WSD` algorithm can be extended by introducing the assumption that some nodes are willing to cooperate with η to disseminate the safety message α. Co-operating nodes are motivated by the fact that the quick dissemination of α will help avoiding potential dangerous situations on the road that these nodes might be involved in. We refer to the scheme where η's neighbors cooperate to propagate the safety message as `Cooperative WSD`.

For the scope of `Cooperative WSD`, we safely assume that all nodes available at the control channel c_3 during the SCH interval (and thus not engaged in any service exchange) will cooperate with η. The set of cooperating nodes (including η itself) during the next SCH interval is referred to as $\mathbf{G}$. The scheduling problem for Cooperative WSD becomes more complicated since it involves multiple nodes. Cooperative WSD is discussed in details in the next section.

6. Cooperative WSD

6.1. Survey: Multi-Purpose Machines scheduling

The scheduling problem in `Cooperative WSD` can be formulated as a parallel multi-purpose machines (MPM) scheduling problem with deadline[37]. In MPM problems, n jobs $J_1, .., J_n$ are to be processed using m identical parallel machines $M_1, .., M_m$. Each job J_j has a processing time of length p_j and a deadline d_j. Only a subset of machines $\mathbf{M_j} \subseteq \{M_1, .., M_m\}$ are capable of processing job J_j. The problem is to schedule each job J_j on a single machine from $\mathbf{M_j}$ in order to minimize $\sum_{j=1}^{n} w_j C_j$, the total weighted completion time. w_j and C_j are respectively the weight coefficient and completion time of job J_j. The three-field notation suggested in [20] is used to represent this problem as follows: $P|M_j, d_j| \sum_{j=1}^{n} w_j C_j$ where P refers to identical parallel machines.

In our problem, the cooperating nodes $\mathbf{G}$ represent the m machines ($m = card(\mathbf{G})$). Channels c_i belonging to $\mathbf{L}$ to be covered represent the n jobs (i.e. $n = card(\mathbf{L})$. To explain how the set $\mathbf{M_j}$ is obtained for each job J_j, we should define first the concept of equivalent nodes at a specific channel c_i. Two nodes $\eta, \delta \in \mathbf{G}$ are said to be equivalent at channel c_i, i.e. $\eta \equiv_{c_i} \delta$, if and only if they share the same subset $\mathbf{N^i}$ of one-hop neighbors at channel c_i. In that case, δ can cooperate with η to disseminate the safety message at channel c_i. In the special case where $\mathbf{G} = \{\eta\}$ which means none of the nodes are cooperating with η, the problem is reduced to a single machine scheduling problem and can be modeled as $1|d_j| \sum_{j=1}^{n} w_j C_j$ as described in the previous section.

Moreover, let's assume that job J_j is to schedule channel c_i at one of the machines in $\mathbf{M_j}$. Then, the set $\mathbf{M_j}$ is the subset of nodes in $\mathbf{G}$ that are equivalent to node η at channel c_i. The processing time p_j and the job weight w_j are set respectively to T_i (channel access delay) and M_i (number of neighbors nodes) which were defined in the previous section. Thus, the optimization function $\sum_{j=1}^{n} w_j C_j$ incorporates the access delay per channel weighted by the number of nodes available at the channel. It can be easily shown that $\sum_{j=1}^{n} w_j C_j$ normalized by the number of neighbors ($card(\mathbf{N})$) represents the average delay to reach a neighbor. This function will be used to minimize the average delivery delay to disseminate the message to a neighbor.

6.2. Workload-balanced Shortest Processing Time first

The MPM problem is strongly NP-hard [29] and thus no Fully Polynomial Time Approximation Scheme (FPTAS) exists unless $P = NP$. In our particular problem, we have a constant upper limit on the number of jobs n since the number of channels in DSRC is constant. The number of cooperating nodes m is not bounded but is expected to take small values, since we do not need more cooperating vehicles than the number of service channels (i.e. 6). For small values of m and n, the problem can be solved efficiently using heuristics, as discussed in [38]. The $P|M_j, d_j| \sum_{j=1}^{n} w_j C_j$ problem involves two decisions [37]: (*i*) choosing the next job $J_j \in \mathbf{L}$ and (*ii*) deciding on which machine from $\mathbf{M_j}$ to schedule the chosen job. A feasible schedule allows the scheduling of all jobs while respecting both deadlines d_j and machine eligibility $\mathbf{M_j}$ constraints. Job deadline d_j is the same for all jobs and is equal to the remaining time till the end of the current service channel interval. Since all jobs in our problem have the same deadline, we do not focus on the deadline constraint in our heuristic. If the adopted schedule does not meet the end of SCH interval deadline, α is re-broadcasted at the start of the next CCH interval to guarantee its reception by all neighbors, as it happens in the current IEEE 1609.4 standard [23].

Due to tight time constraints, we need the processing time of the scheduling algorithm to be close to zero. Thus, we need to keep our heuristic simple and fast to execute in negligible time with current processing capabilities available in target vehicles. Let us define $\mathbf{E}_m$ as the set of eligible jobs to be scheduled on machine M_m. Sets $\mathbf{E}_m$ are easily obtained from sets $\mathbf{M}_j$ discussed earlier.

The first step of the heuristic is to choose from the set $\mathbf{G}$, the available (non-busy) machine M_m with the smallest potential workload. Potential workload W_m is defined as the cardinality of the set $\mathbf{E}_m$. Ties are broken in an arbitrary manner. Then we schedule on the chosen machine in the previous step, the job from the set $\mathbf{E}_m$ with the smallest fraction $\frac{p_j}{w_j}$. Also in this case, ties are broken in an arbitrary manner. After this, we remove the scheduled job from the jobs list and declare the used machine as busy for the amount of time needed to process the scheduled job. We repeat the above mentioned steps until the job list is empty, which means all channels have been scheduled.

Our suggested heuristic referred to as `Workload-balanced Shortest Processing Time first` (WSPT) is illustrated in Algorithm 2.

Algorithm 2: Workload-balanced Shortest Processing Time first (WSPT)

---

repeat

1. Choose the available machine (i.e. the cooperating vehicle) from the set $\mathbf{G}$ with the smallest potential workload W_m.

2. Schedule the job (i.e. the channel) from the set $\mathbf{E}_m$ with the smallest fraction $\frac{p_j}{w_j}$.

3. Remove the scheduled job from $\mathbf{L}$ and declare the used machine as busy for p_j.

until $\mathbf{L} = \emptyset$

6.3. Cooperation Initiation

The proposed `WSPT` heuristic distributes the available jobs among the cooperating nodes in order to minimize the average delivery delay to disseminate the message to a neighbor as described in the previous sub-section. The cooperative nodes need to have a copy of the safety message α and a schedule to follow to distribute this message. Thus, to enable cooperation, node η needs to transmit the safety message at the CCH and piggy-backs the schedule that each cooperating node has to adopt. We refer to the time instant when node η transmits at CCH by the discrete time index t_{coop} where $t_{coop} \in [1, T - T_i + 1]$ (see optimization function proposed in section 5.1). t_{coop} is an important parameter in the Cooperative WSD scheme and we present in the following an algorithm to compute the optimal t_{coop} value. A possible answer is to start cooperation at the earliest possible and thus set $t_{coop} = 1$. In such a case, whenever η has a safety message to transmit, it tunes its RF to the CCH and transmit the safety message along with the cooperation schedule that is generated using the WSPT heuristic.
However, we can foresee a scenario where most of η's neighbors are tuned to a specific channel c_i. Under that scenario, it will be better decision to transmit first at c_i before initiating cooperation. If we revert to the case where no cooperation was assumed, Algorithm 1 provides the schedule to follow based on channels weights. Let's denote by t_{WSD} the time instant to transmit at the CCH according to Algorithm 1. It is easy to show that t_{WSD} constitutes an upper bound on the time to initiate cooperation and thus the following bounds hold: $1 \leq t_{coop} \leq t_{WSD}$. Vehicle η should not delay transmitting at c_3 later than t_{WSD}. However, does

transmitting in the interval $[1, t_{WSD}]$ provide additional gain in terms of minimizing average delay? We propose a simple search algorithm to find the optimal value of t_{coop}. First, set $t_{coop} = t_{WSD}$ and compute the resultant average delivery delay. Decrement t_{coop} by 1 and swap c_3 with the preceding channel in the schedule to check the effect of initiating cooperation earlier in time. If the new schedule provides an improvement in terms of minimizing average delay, then update the value of t_{coop} and repeat this step, else terminate. This algorithm is basically an exhaustive search algorithm, however it is efficient due to the limited size of the search space. The proposed search algorithm is illustrated in Algorithm 3.

Algorithm 3: Search Algorithm

1. Generate single machine schedule using WSD algorithm.
2. Set $t_{coop} = t_{WSD}$.
3. Vary t_{coop} from $t_{WSD} - 1$ to 1.
3.a Execute WSPT and record average delay.
3.b If $E[d_n]$ improves then continue else terminate.

6.4. Algorithm Illustration

At this stage, we will present an example that illustrates the functioning of the Cooperative WSD algorithm. Assume a highway scenario with a node η surrounded by several neighbors. At each CCH interval, η collects `HELLO` messages and builds the sets mentioned in step (1) of the Cooperative WSD algorithm. In this example, $c_\eta = c_6$ and η has two collaborating nodes B and C, and thus $\mathbf{G} = \{\eta, B, C\}$. $\mathbf{L} = \{c_1, c_2, c_3, c_4, c_5, c_6\}$ and then all channels have to be covered except c_0. We assume that the search algorithm instructs η to broadcast first at its current channel and then initiate cooperation by transmitting at channel c_3. Then, the update set of remaining jobs as input to the WSPT heuristics is $\mathbf{L} = \{c_1, c_2, c_4, c_5\}$. Moreover, assume $E_B = \{1\}$, $E_C = \{1, 5\}$ and obviously $E_\eta = \mathbf{L} = \{c_1, c_2, c_4, c_5\}$. At the start of the SCH interval, it turns out that η has an α message in its queue. It starts by broadcasting α at its current channel (c_6 in this case). Then, η switches to c_3 and broadcast α while picky-backing the scheduling assignment identified by WSPT. The cooperating nodes parse the message and retrieve the schedule and act accordingly. Node B has the smallest potential load W_m, and therefore, it is assigned to broadcast at channel c_1 which is removed from $\mathbf{L}$. Node C has the next smallest W_m and it is assigned to broadcast at channel c_5. Two jobs c_2 and c_4 remains in $\mathbf{L}$ with η being the only eligible

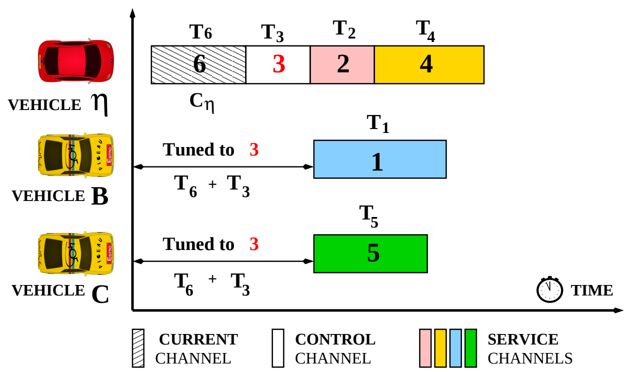


Figure 6: Gantt Chart of the distributed channel scheduler.

machine. We assume that $\frac{p_2}{w_2} < \frac{p_4}{w_4}$ and thus c_2 is scheduled followed by c_4 on η. The Gantt chart in Figure 6 illustrates the resultant jobs scheduling.

7. Performance Evaluation

In the following two sub-sections, we evaluate the performance of the proposed WSD and Cooperative WSD algorithms through a simulation study. To this aim, we use the Network Simulator 2 (Ns-2) extension described in [18] to model multi-channel VANETs. The tool proposed in [18] provides a complete implementation of the IEEE 1609.4 scheme, that can be used on top of the existing ns-2 models of the MAC 802.11p.

7.1. Algorithms Evaluation

We consider the scenario depicted in Figure 3(a), composed by $N+1$ vehicles distributed on a 4-lanes highway. A single vehicle η generates only one event-driven high priority safety message (denoted as α) at a random instant of the `SYNC` interval. All the remaining N vehicles generate background traffic on both service and control channels. During the CCH interval, all the $N+1$ vehicles are tuned to the control channel and broadcasts `HELLO` messages. During the SCH interval, the vehicles might tune their RF to one of the service channels or remain at the control channel. In our simulation model and during SCH interval, each vehicle chooses randomly with an uniform probability distribution to which channel $c_i \in \mathbf{L}$ to tune its RF circuit from the seven DSRC channels. We assume traffic saturation conditions on both control and service channels. We introduce this assumption since we are interested in investigating the performance of safety

Table 2: Simulation Parameters

Number of runs	500
Scenario type	4-lanes highway
Number of vehicles	[4-100]
Vehicle Speed	25 m/s
SCHI length	50 ms
CCHI length	50 ms
Number of channels	7
Packet size	600 bytes
Tx range	300 meters

applications under high load conditions that might compromise the timely delivery of safety messages. Table 2 contains the list of parameters used in our simulation.

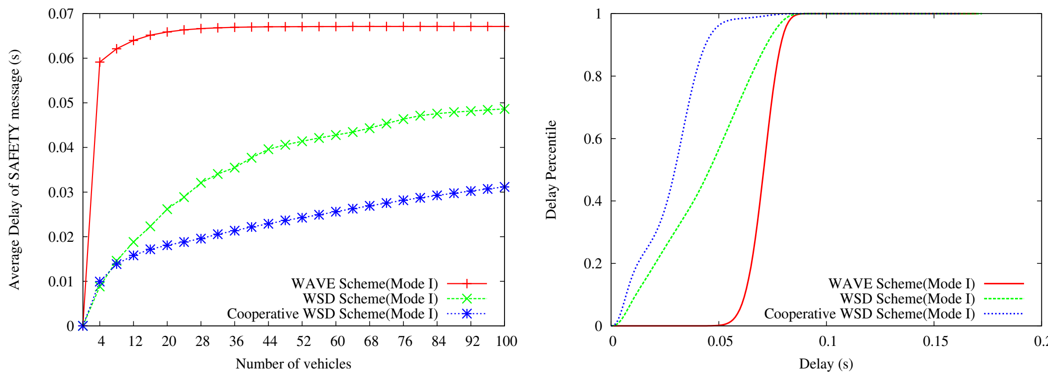
In the following, we implement and compare the performance of three different schemes:

- **WAVE Scheme**: Legacy IEEE 1609.4 scheme considered in the analysis presented in section 4, in which vehicles perform synchronous switching between CCH and SCH intervals. Message α can be broadcasted only during the CCH interval on the control channel.

- **WSD Scheme**: WAVE-enhanced Safety message Delivery scheme (WSD) described in Section 5. Set $\mathbf{G} = \{\eta\}$ which means none of the nodes are cooperating with η to disseminate the message α during SCH interval.

- **Cooperative WSD Scheme**: Cooperative WAVE-enhanced Safety message Delivery scheme described in section 6 in which the vehicle η tries to deliver the α message during the SCH interval and relies on cooperation with other vehicles tuned to the control channel during SCH interval.

We investigate the performance of safety-related applications using these two metrics: (*i*) end-to-end *Delay* defined as the average time from the α message generation at the application layer at vehicle η to when it is received by a neighbor vehicle, and (*ii*) *Probability of Successful Delivery* (PSD) defined as the probability that a neighbor vehicle will successfully receive the α message from vehicle η. Also similar to section 4, we distinguish between two modes in the performance



(a) (b)

Figure 7: The average delay and the delay percentile (using 40 active vehicles) when the message is generated during the SCH interval (Mode I) are shown in Figures 7(a) and 7(b) respectively.

evaluation, *Mode I* and *Mode II*, based on the interval (SCH and CCH respectively) during which the α message is generated.

Mode I. Vehicle η generates the α message at the start of the SCH interval. Figure 7(a) shows the average delivery delay as a function of the number of vehicles for the three different schemes we are considering in our analysis. WAVE Scheme(Mode I) introduces high delay overhead since we always buffer α till the start of the next CCH interval and then contend for the medium to transmit. Both WSD Scheme(Mode I) and Cooperative WSD Scheme(Mode I) overcome this limitation by transmitting α directly during the SCH interval on different service channels. Figure 7(a) shows that Cooperative WSD Scheme(Mode I) is able to provide a delay reduction of more than 30% compared to the WSD Scheme, and more than 50% compared to the legacy WAVE Scheme. Figure 7(b) provides a complementary view of the system performance, by showing the delay percentile in a configuration with 40 active vehicles. Figure 8(a) shows the PSD as a function of the number of vehicles for the three evaluated schemes. Results in Figure 8(a) reveal that both WSD and Cooperative WSD Schemes provide higher probability of successful delivery of the α message than the standard WAVE Scheme. The performance improvement increases with the number of vehicles. This can be justified considering the characteristics of the channel allocation enforced by the 1609.4 scheme. During the CCH interval, all the vehicles contend on the same channel, while during the SCH interval the number of active nodes on the same channel is (on average) divided by seven. As a result, vehicle η witnesses higher

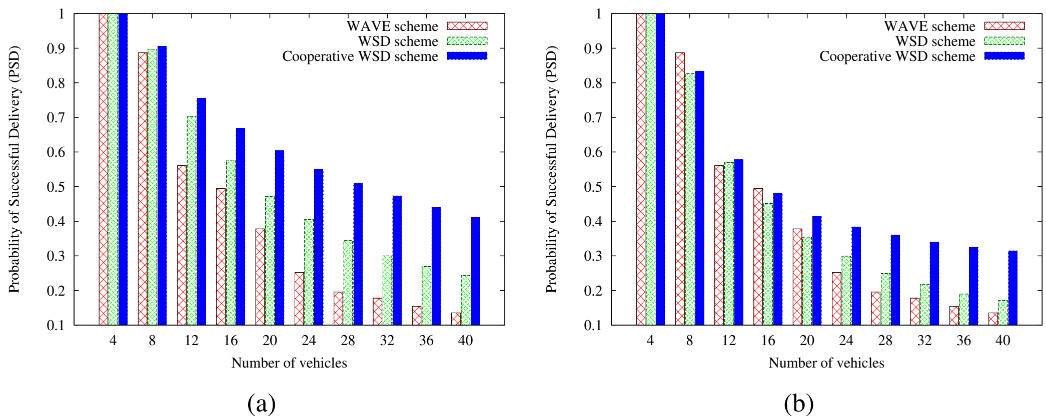
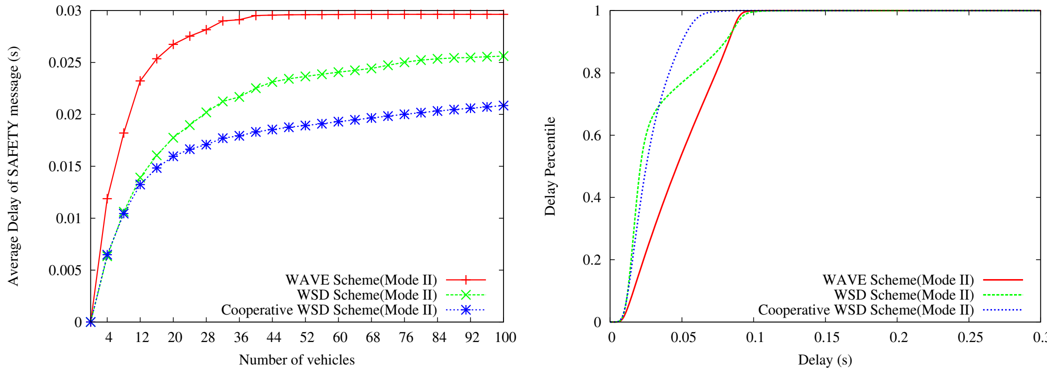


Figure 8: The PSD metric when the message is generated during the SCH interval (Mode I) and during the CCH interval (Mode II) are shown in Figures 8(a) and 8(b) respectively.

successful packet delivery probability using both WSD and Cooperative WSD Schemes. Cooperation gains are evident under increasing traffic density conditions, since more vehicles are tuned to channel c_3 during the SCH interval, and thus contribute to the dissemination process described in Algorithm 2

Mode II. Vehicle η generates the α message at a random interval during the CCH interval. Figure 9(a) shows the average delivery delay as a function of the number of vehicles for the three different schemes described above. WAVE Scheme(Mode II) might suffer from significant delay overhead due to the high Packet Un-transmitted Risk Index (PURI). Un-transmitted packets are buffered and transmitted at the start of the next CCH interval. In both WSD Scheme(Mode II) and Cooperative WSD Scheme(Mode II), we alleviate the delay problem by allowing the delivery of un-transmitted packets during the next SCH interval directly. Figure 9(a) reveals that Cooperative WSD Scheme can provide a delay reduction of more than 30% when compared to the standard WAVE Scheme. Figure 9(b) completes the delay analysis by depicting the percentile delay in the configuration with 40 active vehicles. Finally, Figure 8(b) confirms the improvement provided by the WSD Scheme in terms of PSD using *Mode II*.

In Figures 10(a) and 10(b) we further investigate the performance of the Cooperative WSD Scheme(ModeI), in terms of cooperation percentage and cooperation initiation time. We assumed so far that all the vehicles available at the control channel c_3 during the SCH interval (and thus not engaged in any service exchange) will cooperate with the transmitting vehicle η. However, this might not be the



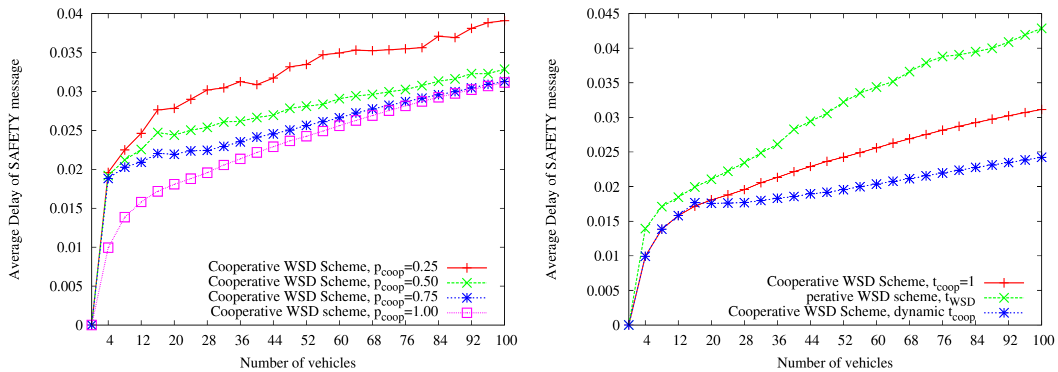
(a) (b)

Figure 9: The average delay and the delay percentile (using 40 active vehicles) when the message is generated during the CCH interval (Mode II) are shown in Figures 9(a) and 9(b) respectively.

case in presence of selfish behaviours. We model this situation in Figure 10(a), in which we depict the average delay of Cooperative WSD Scheme(Mode I) when considering different probability of cooperation (p_{coop}) from neighbouring vehicles of η. The configuration with p_{coop}=1.0 corresponds to the default setting used so far. It is easy to see that the dissemination delay is reduced for higher values of p_{coop}. Moreover, for $p_{coop} > 0.25$, the performance difference among different configurations of the Cooperative WSD Scheme decreases under moderate and high vehicular density conditions, since enough vehicles are found on the c_3 channel to disseminate the message over the remaining SCH channels. In Figure 10(b) we investigate the impact of cooperation initiation time (i.e. the t_{coop} parameter discussed in Algorithm 3) on the average delay. We consider three different configurations: (*i*) t_{coop}=1, i.e. cooperation is used as first step by vehicle η, (*ii*) t_{coop}=t_{WSD}, i.e. cooperation is delayed till the upper bound specified by WSD scheme, and (*iii*) *dynamic* t_{coop}, i.e. cooperation initiation time is decided dynamically according to Algorithm 3. Figure 10(b) reveals that the dynamic approach provides the best performance in terms of dissemination delay, since it allows the transmitting vehicle η to determine the best trade-off between cooperation exploitation and overhead mitigation, by taking into account the current distribution of vehicles on the service channels.

7.2. WSPT Heuristic Evaluation

All analysis performed in the previous subsection use the WSPT heuristic described in Algorithm 2. In this subsection, we introduce two different heuristics



(a) (b)

Figure 10: The impact of p_{coop} and t_{coop} on the performance of Cooperative WSD Scheme(Mode I) are shown in Figure 10(a) and 10(b), respectively.

and compare its performance with WSPT to show the superiority of the latter.

The Workload-balanced Shortest Processing Time first (WSPT) heuristic described in Algorithm 2 takes into account both the number of neighbors $card(\mathbf{N_{c_i}})$ tuned to each channel as well as the channel access time T_i. As a result, it is able to greatly reduce the average delay to disseminate the safety message to a neighbor when compared with other policies that do not take into account the specific load conditions on each channel. We introduce here two heuristics refereed to as `Random Selection` and `Largest Neighbors First` and defined as follows:

- *Random Selection*: Vehicle η randomly picks up a service channel, and assigns it randomly to one of the nodes in set $\mathbf{G}$.
- *Largest Neighbors First*: Vehicle η starts by scheduling the channel with the largest number of neighbors tuned to it. Then, assign it to the set of cooperating vehicles (including η itself) in a round robin way.

Figure 11 shows the average delay experienced by each of the three different heuristics defined above. We can see that WSPT outperforms the other heuristics and leads to smaller delay as expected.

8. Conclusions

In this paper, we investigated the performance of safety applications over multi-channel VANETs. Through a combination of analytical analysis and sim-

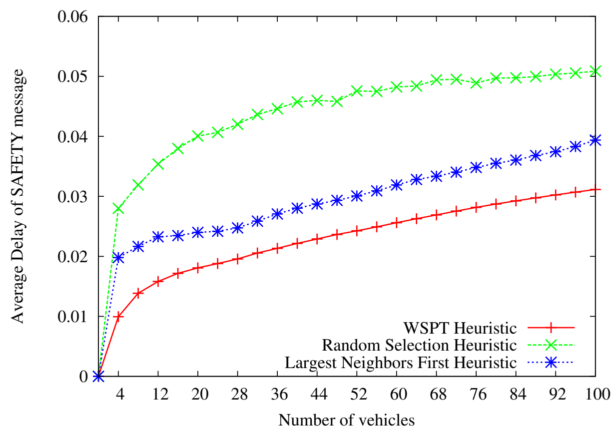


Figure 11: Comparison of the average delay of WSPT heuristic with two other suggested heuristics.

ulation results, we revealed some drawbacks of the current IEEE 1609.4 WAVE standard that might compromise the practical realization of vehicular applications with strict delay requirements. For this purpose, we investigated the problem of guaranteeing efficient broadcast communication on multi-channel single-radio VANET environment. Then, we proposed a WAVE-enhanced Safety message Delivery scheme (WSD) that provides fast dissemination of safety message in 1609.4-based VANETs, while preserving compatibility with the existing WAVE standard. The proposed scheme attempts to minimize the delivery delay of safety message through a novel forwarding paradigm and a distributed channel scheduling. We then extend WSD by enabling cooperation between nodes to disseminate safety messages. Future works include the extension of the proposed paradigm to multi-hop environment and its implementation on small-scale vehicular testbed.

References

[1] I. F. Akyildiz, X. Wang, and W. Wang. Wireless Mesh Networks: A Survey. *Elsevier Computer Networks Journal*, 47(4), pp. 445-487, 2005.

[2] M. Amadeo, C. Campolo and A. Molinaro. Enhancing IEEE 802.11p/WAVE to provide infotainment applications in VANETs. *Ad Hoc Networks*, 10(2), pp. 253-269, 2010.

[3] A. Amoroso, G. Marfia and M. Roccetti. Going Realistic and Optimal: A Dis-

tributed Multi-Hop Broadcast Algorithm for Vehicular Safety. *Computer Networks (Elsevier)*, 55(10), pp. 2504-2519, 2011.

[4] G. Bianchi Performance Analysis of the IEEE 802.11 Distributed Coordination Function *IEEE Journal on Selected Areas in Communications*, 18(3), pp. 535-547, 2000.

[5] L. Butty, T. Holczer and I. Vajda. On the effectiveness of changing pseudonyms to provide location privacy in VANETS. *Proc. of ESAS*, Cambridge, 2007.

[6] F. Cali', M. Conti and E. Gregori. Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit. *IEEE/ACM Transactions on Networking*, 8(6), pp. 785-799, 2000.

[7] C. Campolo, A. Molinaro and A. Vinel. Understanding the Performance of Short-lived Control Broadcast Packets in 802.11p/WAVE Vehicular Networks. *Proc. of IEEE VNC*, Amsterdam, pp. 1-8, 2011.

[8] M. Di Felice, R. Doost-Mohammady, K. Chowdhury and L. Bononi. Smart Radios for Smart Vehicles. In *IEEE Vehicular Technology Magazine*, 7(2), pp. 26-33, 2012.

[9] M. Di Felice, A. J. Ghandour, H. Artail and L. Bononi. On the Impact of Multi-channel Technology on Safety-Message Delivery in IEEE 802.11p/1609.4 Vehicular Networks. *Proc. of IEEE ICCCN*, Munich, 2012.

[10] M. Di Felice, A. J. Ghandour, H. Artail and L. Bononi. Enhancing the performance of safety applications in IEEE 802.11p/WAVE Vehicular Networks. *Proc. of IEEE WoWMoM*, San Francisco, 2012.

[11] Draft Guide for Wireless Access in Vehicular Environments - Architecture, IEEE P1609.0/D5, September 2012.

[12] Draft Standard for Wireless Access in Vehicular Environments - Provider Service Identifier (PSID) Allocations, IEEE P1609.12/D0.3, May 2011.

[13] S. Eichler. Performance Evaluation of the IEEE 802.11p WAVE Communication Standard. *Proc. of IEEE VTC-Fall*, Baltimore, pp. 2199 - 2203, 2007.

[14] EuroFOT EU project. http://www.eurofot-ip.eu. FP7.

[15] M. Gerlach and F. Guttler. Privacy in VANETs using Changing Pseudonyms - Ideal and Real. *Proc. of IEEE VTC*, Dublin, pp. 2521-2525, 2007.

[16] K. Fawaz, A. Ghandour, M. Olleik, H. Artail. Improving reliability of safety applications in vehicle ad hoc networks through the implementation of a cognitive network. *Proc. of IEEE ICT*, Doha, pp. 798-805, 2010.

[17] A. J. Ghandour, K. Fawaz and H. Artail. Data Delivery Guarantees in congested Vehicular Ad Hoc Networks using cognitive networks. *Proc. of IEEE IWCMC*, Turkey, 2011.

[18] A. J. Ghandour, M. Di Felice, H. Artail and L. Bononi. Modeling and Simulation of WAVE 1609.4-based Multi-channel Vehicular Ad Hoc Networks. *Proc. of ACM SIMUTools*, March 19-23, 2012, Sirmione-Desenzano, Italy.

[19] S. Grafling, P. Mahonen and J. Riihijarvi. Performance evaluation of IEEE 1609 WAVE and IEEE 802.11p for vehicular communications. *Proc. of IEEE ICUFN*, Jeju Island, pp. 344 - 348, 2010.

[20] R. Graham, E. Lawler, J. Lenstra and K. 21Rinnooy. Optimization and approximation in deterministic sequencing and scheduling: a survey. *Ann Discrete Math*, 5(2): pp. 287-326, 1979.

[21] M. Hassan, H. Vu and T. Sakurai. Performance Analysis of the IEEE 802.11 MAC Protocol for DSRC Safety Applications. *IEEE Transactions on Vehicular Technology*, 60(8), pp.3882-3896, 2011.

[22] K. Hong, J. B. Kennedy, V. Rai and K. P. Laberteaux. Evaluation of Multi-Channel Schemes for Vehicular Safety Communications. *Proc. of IEEE VTC-Spring*, Taipei, pp. 1-5, 2010.

[23] IEEE Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation. *IEEE Std 1609.4-2006*, 2006.

[24] IEEE 1609.3-2010, IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services, December 2010.

[25] D. Jiang and L. Delgrossi. IEEE 1609.4 DSRC Multi-Channel Operations and Its Implications on Vehicle Safety Communications. *Proc. of IEEE VNC*, Tokyio, pp. 1-8, 2009.

[26] T. Kawaguchi and S. Kyan. Worst case bound of an LRF schedule for the mean weighted flow-time problem. *SIAM J. Computing*, 15(4), pp. 1119-1129, 1986.

[27] R. Lasowski and R. Schmidt. A Multi-Channel Beacon Forwarding Approach in Dual Radio Vehicular Ad-Hoc Networks. *Proc. of IEEE IVS*, pp. 522-525, 2011.

[28] U. Lee and M. Gerla. A survey of urban vehicular sensing platforms. *Computer Networks (Elsevier)*, 54(4), pp. 527-544, 2010.

[29] J.Y.-T. Leung and C.-L. Li. Scheduling with processing set restrictions: a survey. *Int. Journal of Production. Economics*, 116(2), pp. 251-262, 2008.

[30] T. K. Mak, K. P. Laberteaux, R. Sengupta and M. Ergen. Multichannel Medium Access Control for Dedicated Short-Range Communications. *IEEE Transactions on Vehicular Technology*, 58(1), pp. 349-366, 2009.

[31] J. Misic, G. Badawy and V. Misic. Performance Characterization for IEEE 802.11p Network with Single Channel Devices. *IEEE Transactions on Vehicular Technology*, 68(4), pp. 1775-1789, 2011.

[32] A. Raniwala and T.C. Chiueh. Architecture and Algorithms for an 802.11-based Multi-Channel Wireless Mesh Network. *Proc. of IEEE Infocom*, pp. 2223-2234, Miami, 2005.

[33] M. Raya and J.-P. Hubaux. The Security of Vehicular Ad Hoc Networks. *Proc. of 3rd ACM Workshop on Security of Ad Hoc and Sensor Networks*, pp. 11-21, November, 2005.

[34] W.E. Smith. Various Optimizers for Single-stage Production. *Naval Res. Logist. Quart. 3. page 59-66, 1956.*

[35] J.-K. Song, C.-H. Lee, M.-S. Woo and S.-G. Min. Distributed Periodic Access Scheme (DPAS) for the Periodic Safety Messages in the IEEE 802.11p WAVE. *Proc. of CMC*, Qingdao, pp. 465-468, 2011.

[36] J.P. de Sousa and L.A. Wolsey A time-indexed formulation of non-preemptive single-machine scheduling problems. Mathematical Programming 54, pp. 353-367, 1992.

[37] L. Su. Scheduling on identical parallel machines to minimize total completion time with deadline and machine eligibility constraints. *International Journal of Advanced Manufacturing Technology*, 40(5), pp. 572-581, 2009.

[38] G. L. Vairaktarakis and X. Cai. The value of processing flexibility in multipurpose machines. *IIE Transactions*, 35(8), 763-774, 2003.

[39] J.M. van den Akker, C.P.M. van Hoesel, and M.W.P. Savelsbergh. A polyhedral approach to single-machine scheduling problems. Mathematical Programming, 1997

[40] Q. Wang, S. Leng, H. Fu and Y. Zhang. An IEEE 802.11p-based Multichannel MAC Scheme with Channel Coordination for Vehicular Ad Hoc Networks. *IEEE Transactions on Intelligent Transportation Systems*, 99(1), pp. 1-10, 2011.

[41] T. L. Willke, P. Tientrakool and N. F. Maxemchuk. A Survey of Inter-Vehicle Communication Protocols and Their Applications. *IEEE Communications on Surveys and Tutorials*, 11(2), pp. 3-20, 2009.

[42] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Wireless Access in Vehicular Environment *IEEE Std 802.11p/D7.0*, 2009.