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Mickaël Riviere*, José D. Padrón†, Carlos T. Calafate†, Juan-Carlos Cano†, and Tahiry Razafindralambo*
* Reunion Island and Indian Ocean Engineering School (ESIROI), University of Reunion Island, Reunion Island, France
E-mail: mickael.riviere@esiroi.re, tahiry.razafindralambo@univ-reunion.fr
† Computer Engineering Department (DISCA), Universitat Politècnica de València, 46022 Valencia, Spain
E-mail: {jdpadper,calafate,jucano}@disca.upv.es

***Abstract*—Vehicular networks have emerged in the past years as one of the most promising technologies in the context of Intelligent Transportation Systems. Several applications have recently been envisaged to improve the lives of citizens in different ways, particularly in the field of safety. In this work we focus on a different direction by leveraging on vehicular communication technologies and software-defined networking (SDN) to achieve a solution able to improve the travel time of emergency vehicles (EVs) when traveling in urban environments. In particular, we devise a solution where the route to be followed by EVs is shared with an SDN-enabled infrastructure, being then smartly rebroadcasted using those roadside units (RSUs) that fall within the region the EV will pass by in a near future. This way, standard vehicles that are ahead of the EV are notified about its arrival, and clear the required lane to facilitate a faster and obstacle free path for the EV's journey. Simulation experiments based on the SUMO traffic simulator for the city of Valencia, Spain, show that, if properly tuned, the proposed solution is able to reduce the travel time of EVs by nearly 15%, while maintaining the travel time of other vehicles mostly unaltered.**

***Index Terms*—Software-Defined Networks; SUMO; V2X; emergency vehicles; DENM messages.**

I. Introduction

The field of Intelligent Transportation Systems (ITS) is gaining momentum due to its potential at improving the lives of citizens from many perspectives, including timeliness, efficiency, fuel economy, environmental friendliness, etc. [1]. In this context, vehicular ad hoc networks (VANETs) [2] have emerged as a means for vehicles to directly communicate with each other, or with the aid of infrastructure elements known as RoadSide Units (RSUs) [3]. Such networks pave the way for a plethora of services such as safety, real-time traffic monitoring, congestion detection, information and entertainment, etc. [4].

Recently, the adoption of Software-Defined Networking (SDN) in VANET environments has emerged as a solution to provide improved flexibility and programmability to these networks [5], [6]. In this context, advanced services can be envisioned that involve a high level of network dynamism. Hence, in this paper, we focus on a novel application that combines the strengths of SDN and VANETs to reduce the travel time of emergency vehicles (EVs) in urban environments. In particular, we focus on situations where the traffic density in a city is moderate or high, which often causes an emergency vehicle to travel slower than expected as other vehicles often do not know exactly which action to take when they detect its presence, and such detection often occurs only when the EV is already quite near. The proposed solution addresses this problem by partially sharing the EV's established path with other vehicles via Decentralized Environmental Notification Messages (DENM) [7]. Such solution is possible by combining VANET communications with SDN, whereby messages are sent from the EV to the nearest RSU, and then from another RSU to the relevant vehicles along the path (V2I communications paradigm). In particular, the use of SDN technology will enable a smart and dynamic redirection of DENM messages to warn road users ahead that an EV is approaching, and that a specific lane must be cleared to facilitate its trip. An optimized redirection of DENM messages promotes the reduction of network traffic by broadcasting only the DENM messages at relevant points, and reaching only those receivers that should actually take an action on the messages, instead of merely targeting all vehicles in circulation indiscriminately. This helps at drastically reducing the radio resources' consumption, being a significant contribution of the current work compared to prior approaches.

Our solution has been implemented and validated by combining the Ryu SDN controller [8] with the SUMO traffic simulator [9]. Based on experiments in the city of Valencia, Spain, we are able to show that the proposed solution is quite effective, allowing to reduce the travel time of EVs by nearly 15%. In addition, we find that our solution does not introduce a meaningful penalty for other vehicles circulating along the EV's route, being that their travel times remains similar.

The remainder of the paper is organized as follows: in the next section we provide an overview of some related works. Then, in section III, we provide an overview of our proposal, including also technical details regarding its implementation. Section IV details the simulation framework we have set forth in order to undertake the desired study. Experimental results are then presented and discussed in section V. Finally, conclusions and future research directions are provided in Section VI.

II. Related work

The improvement of the emergency services is an issue that has been addressed by several research projects. In particular, we can find in the literature different works where VANET technologies are leveraged to reduce the travel times of EVs. Back in 2009, Buchenscheit et al. [10] introduced the concept of active warnings for EVs to notify other vehicles about their needs. Years later, Jayaraj and Hemanth showed the potential of VANETs for emergency vehicle signaling [11]; this solution uses DSRC communication to warn nearby vehicles, and facilitate the passage of the EV. Such approach was extended more recently [12] by shifting the focus to RSUs.

The focus on traffic lights is another approach that can be beneficial to bring down the travel time of EVs [13]. In this direction, Sumi and Ranga [14] proposed an IoT-VANET-based traffic management system that will ease traffic movements for EVs. Similarly Costa et al. [15] proposed a system that uses the current infrastructure of the transceivers in traffic lights and the features of DSRC/ITS-G5 to provide communication between the EVs and the transceivers in traffic lights.

RF signals can also be used to segregate a certain part of a road, hence reducing the traffic on the EV's route [16]. Other solutions exist to secure the messages that are exchanged using various encryption methods and security algorithms; such methods enable traffic discovery so that messages exchanged between the EVs and the vehicles cannot be diverted, and may influence the actual traffic [17]. However, these different solutions have little or no effect on traffic to facilitate the movement of emergency vehicles. Indeed, they simply collect information and adapt the EV's route accordingly.

In this paper, our approach follows the same research line as that in [14], [15], emphasizing on V2I communications to improve EV travel times. In particular, the proposed solution will use an SDN network to dynamically handle both short and long range messages, avoiding message broadcasting in areas where the notification has little or no relevance. Hence, our solution will warn vehicles on the same stretch of road to move away, but will also warn vehicles ahead along the EV's route that an incoming EV is expected; this allows freeing up lanes so that the entire EV route can benefit from reduced travel times, while minimizing the usage of radio resources.

III. Proposed solution

VANET technologies are capable of offering support for advanced services, which may, for instance, help to improve traffic efficiency. To this end, the use of Cooperative Awareness Messages (CAM) and DENM messages [7] can be used to gather periodic status data from nearby vehicles, or to provide safety services such as cooperative collision avoidance. DENM messages are often generated by a Central ITS service manager following a request from one of the services that requires the notification of an asynchronous event. In a decentralised situation, specific details of the event informed in the message can warn us about the level of danger using a set of four possibilities: *informative, obstacle, danger, the highest danger*.

This paper attempts to provide a solution to improve the travel time of EVs by combining the Vehicle to Infrastructure (V2I) and Infrastructure to Vehicle (I2V) paradigms, along with SDN technology, to achieve as optimized communications solution. In particular, SDN will support the exchange of DENM messages between the EV and other road users through the vehicular infrastructure; such messages will notify vehicles about the imminent lane occupancy of the EV in their vicinity, allowing them enough time to free that lane before the EV's arrival.

To understand how this goal is achieved, Figure 1 shows an overview of the proposed network architecture. The network infrastructure includes an edge domain where SDN-enabled Roadside Units (RSUs) are located at the lower infrastructure layer, and whose connectivity is made possible by the higher infrastructure layers, all of them managed by the SDN controller. Whenever the EV detects a new RSU, it will contact it to announce its future route. Such information is sent upwards to the SDN controller, which exchanges this information with a specific ITS application developed for our solution. Such application includes geographic data about each of the RSUs deployed. Based on such data, it decides which RSU (or RSUs) is/are the best candidate(s) to disseminate the received message. Such selection is detailed in Algorithm 1. Its operation is quite simple; first, it must retrieve several data about the EV, such as its position, the lane ID, or the last RSU visited. The algorithm will then use this information to determine the next RSU along the path. If the EV starts its journey and does not know any RSU, then the one with the highest signal strength is chosen. Once the next RSU(s) is chosen, a message is sent with the necessary information to warn the other vehicles.

Afterward, such information is provided to the SDN controller, which reconfigures the flow tables of switches and RSUs, thereby defining the new path for this flow. From this point on, the DENM message that triggered this reconfiguration, as well as all other DENM messages that follow (when arriving from the same RSU), will be delivered to the target RSU(s), which will broadcast them. Since the goal is to empty the lane that the EV is using, all vehicles traveling in that same lane will be requested, upon message reception, to change their lane, so as to free the EV's lane for a period τ. This is the case of vehicle C in the figure.

As final remarks regarding this solution, it is worth noting that it is applicable to large cities, where major streets and avenues have more than one lane for a certain travel direction. Also, for safety and abuse prevention purposes, only an EV can send messages requesting the release of a lane. Standard vehicles can only receive messages and act upon them. In addition, when receiving a lane change message, this can result in a mere warning to the driver for standard vehicles, or a mandatory instruction in the case of autonomous vehicles. Regarding the period of time τ during which the lane is

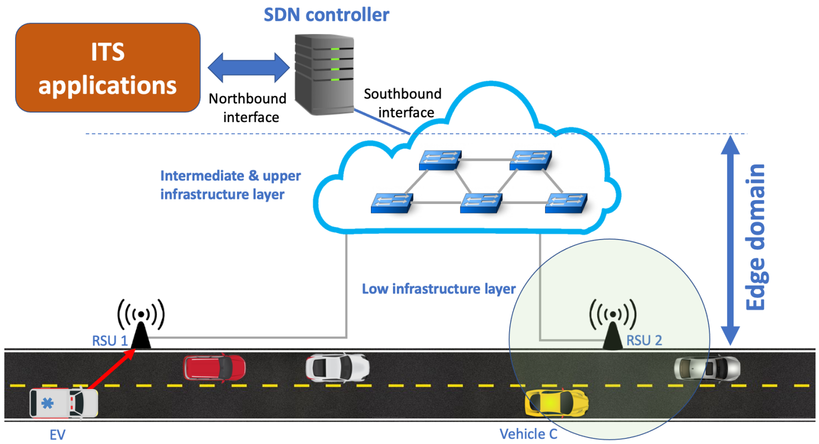


Fig. 1: Proposed network architecture.

Algorithm 1 RSU selection algorithm

```
Data: p: a new EV position; rsuHistory: a record of previous
      RSU visited; evLane: the actual EV lane
Result: A message is sent to the next RSU on the route.
while true do
    if p ≠ null & rsuHistory then
        lastRSU = calcDistance(ev,rsuHistory)
        for rsu in network do
            distance = calcDistance(ambulance,rsu)
            if distance ≤ lastRSU then
                nextRSU = rsu
            end
        end
    else
        nextRSU = SSF(rsu[])
    end
    if nextRSU ≠ lastRSU then
        rsuChoiceMessage = p + nextRSU + lane
        controller.send(rsuChoiceMessage)
        lastRSU = nextRSU
    end
end
```

requested to be empty, the EV can select it based on its travel predictions.

IV. Simulation Framework

In this section we will describe the simulation framework used for our study, which involves three different tools:

i) Mininet version 2.3.0 [18], in order to emulate the network.
ii) Ryu version 4.34 [8], which serves as an external controller to the network.
iii) SUMO version 1.14.1 [9], which allows us to simulate the traffic within a city.

Firstly, Mininet allows us to design and emulate the proposed network. To this end, we devise a tree topology consisting of 4 switches (openVSwitch) and 8 access points. Notice that Mininet is capable of working with the OpenFlow technology, which is a basic requirement for our SDN-based solution.

Secondly, the RYU controller allows the dynamic creation of the flow table entries, and the redirection of the various network messages. This allows us to dynamically redirect messages towards the next RSU along the EV's route by having awareness of the current EV position, the geographic location of all RSUs, and the EV route itself, determining the most appropriate RSU at any time.

Thirdly, SUMO is used for the simulation of the road, specifically to recreate a part of the city of Valencia. It is worth mentioning that the vehicles simulated on SUMO are also connected to Mininet in order to identify them as mobile network hosts. A total of 200 cars are present in the simulation, and they constantly move along a randomly-defined path along the streets of the city.

The behavior of the simulation is the following. A car will have to make a journey from a point A to a point B. Each time it detects a new RSU, it will send a message (DENM) to the controller. Following an analysis by the ITS application, this message will be then redirected to the next RSU placed strategically along the EVs path, being received by all the vehicles within its radio range. Such vehicles should react to the message by switching to another lane whenever they can interfere with the EV.

To have a complete view of the proposed simulation framework, Figure 3 shows a diagram of our network and the different tools involved. The main goal is that the EV sends its DENM to the SDN controller through the RSUs deployed throughout the city, and the different intermediate equipment of the SDN network. The message will then be redirected to the next access point and retransmitted to the other vehicles.

Using the devised simulation framework, we are able to study the impact of varying different parameters on the EV travel time performance, and we can also measure network metrics like network (re)configuration time, message redirection delay, and number of packets involved.

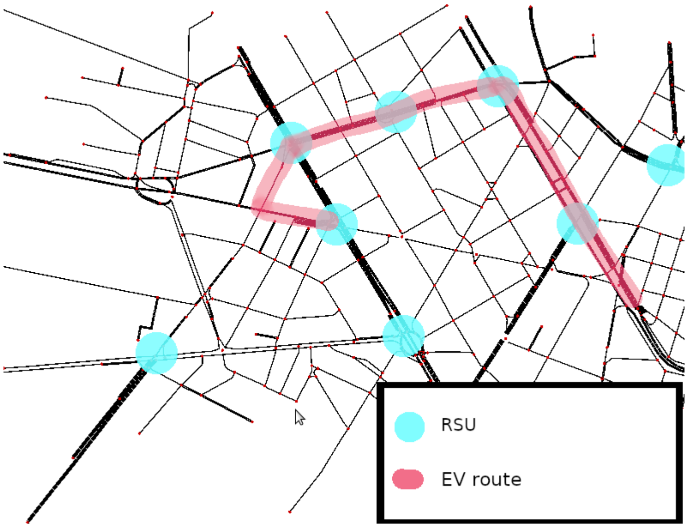


Fig. 2: Scenario used for testing. Blue circles indicate the location of the RSUs, and the EV's route is shown in red.

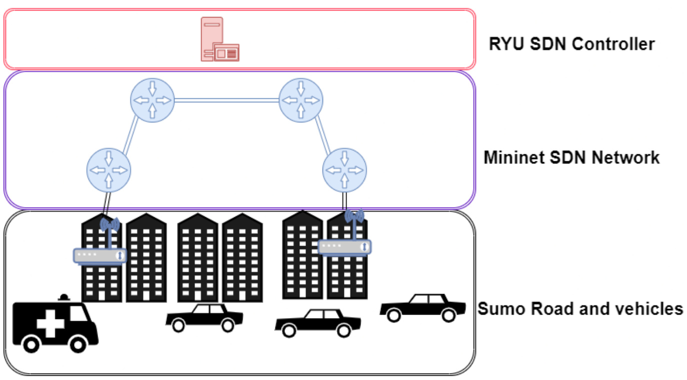


Fig. 3: Simulation framework.

TABLE I: Average speed and travel time for the EV when varying the τ parameter.

	Default	$\tau = 20$	$\tau = 30$	$\tau = 40$	$\tau = 50$	$\tau = 60$
Avg. speed (m/s)	8.38	9.17	9.25	9.64	9.73	9.54
Δ (m/s)	-	+0.79	+0.87	+1.26	+1.35	+1.16
Δ(%)	-	+9.42	+10.38	+15.03	+16.11	+13.84
Travel time (s)	180	164	166	159	155	161
Δ (s)	-	-16	-14	-21	-25	-19
Δ(%)	-	-8.88	-7.77	-11.66	-13.88	-10.55

TABLE II: Average travel time for regular vehicles when varying the τ parameter.

	Default	$\tau = 20$	$\tau = 30$	$\tau = 40$	$\tau = 50$	$\tau = 60$
Travel time (s)	185.6	186.1	187.4	187.6	186.7	187.4
Δ (s)	-	+0.5	+1.8	+2.0	+1.1	+1.8
Δ(%)	-	+0.27	+0.97	+1.08	+0.59	+0.97

V. Simulation Results

In this section we present our simulation results based on the simulation framework described in the previous section. Our goal is to determine the degree of effectiveness of our SDN-based solution, where algorithm 1 is used to optimize traffic, compared to the default situation, where no mechanism is available to favor the EV along its path. To this end we perform different experiments under similar conditions, and where we vary the period τ, which allows us to regulate for how long does the EV request a specific lane to be left empty, a period of time that should be respected by other vehicles. In particular, we test with τ values of 20, 30, 40, 50 and 60 seconds (one for each experiment).

Regarding performance metrics, a comparison between the EV and regular vehicles in terms of travel time and average speed will be carried out. This is in order to see if an improvement is visible, and what is the impact of our approach on the global traffic. In particular, our end goal is to reduce the EV's travel time as much as possible while attempting to maintain the impact on the other vehicles to a minimum.

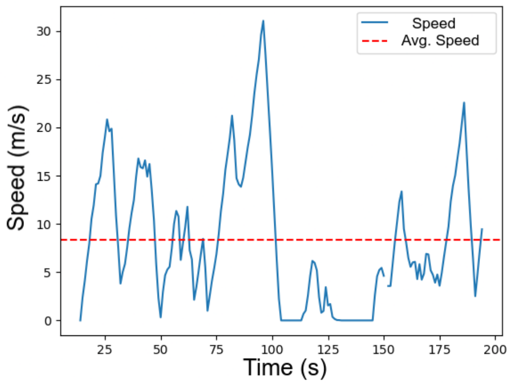
Having said this, we start by first analyzing the travel time and average speed of the EV to determine the actual improvements achieved when adopting different values for the τ parameter.

Table I shows the different values achieved in terms of average speed and travel time for each value of τ, being the default situation (no SDN network) available as reference. In terms of average speed, we can observe a tendency (from 20 to 50s); in particular, when τ is increased, the average speed also increases. In fact, the optimal results are achieved for $\tau = 50$, which results in an average speed of 9.73 m/s; this is 16.11% faster than the default situation. Likewise, the lowest value obtained ($\tau = 20$) still allows obtaining a better performance than the default situation, with an average speed that is 9.72 % higher.

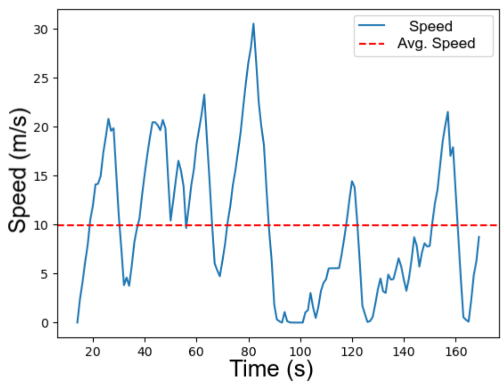
In terms of travel time, we can see the same trend than for the average speed, only in the opposite direction. Again the best value is also achieved for $\tau = 50$. For this time period, the travel time decreases by 25 seconds, a 13.88% less than the default situation.

In order to contrast the results, figure 4 shows the variation of the speed of the EV throughout time. In particular, it shows the difference between the default situation (figure 4a), and the best-case situation, achieved for $\tau = 50$ (figure 4b). In the latter experiment we can see that, from the beginning of the EV's movement, the average speed experienced is higher. In addition, there are also fewer times when the EV has to slow down or stop completely.

It is expected that improving the EV travel time has an impact on the overall traffic, has vehicles have to move aside in order to clear a specific lane; this is prone to cause more temporary congestion to regular vehicles. So, an ideal solution should reduce the EV's journey time while minimizing the impact on the global traffic.



(a) Default situation



(b) $\tau = 50$

Fig. 4: EV speed vs. time.

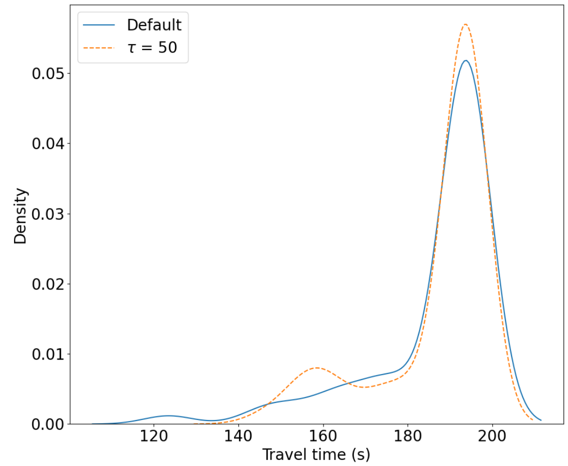


Fig. 5: Distribution of travel time for regular vehicles (Default vs $\tau = 50$).

TABLE III: Network performance stats.

Message redirection time	6005.4 ms ± 0.34%
Network configuration time	1260 ms ± 8.63%
Average number of vehicles reached	69
Number of packets exchanged	234 ± 16.46%

If we focus on the results available in table II, we can observe the behavior of the overall traffic regarding travel time. As we can observe, the impact is minimal. In fact, the average travel time when compared to the default situation increases, at most, by 1.08 % (for $\tau = 40$); for the optimum value found above ($\tau = 50$), we see that such increase is limited to 0.59 %, which can be considered nearly negligible. To gain further insight onto the differences between the default situation and the optimal one, figure 5 shows the distribution of the travel time for vehicles in both cases. Notice that, for the default situation, the minimum values are lower, and there are slight differences around 160s and 195s, meaning that travel times tend to concentrate around these values as a result of having fewer available lanes, which means that more queuing is prone to occur to leave room for the EV, as expected.

Overall we find that, in order to achieve a correct balance between the EV trip optimization and the impact on the rest of the traffic, a 50s lane reservation period seems to be a good compromise. In this way, we will obtain a travel time improvement of 25s for the EV in a 3-minute route, being that other vehicles only experience an increase of about 1 second (on average).

Finally, the question arises as to the network's ability to manage all its connections from a global system perspective. As it can be seen in table III, acceptable values are achieved, although these could be improved with better/dedicated hardware. Notice that we are in a situation where a single controller manages 12 network devices that simultaneously receive information from 200 vehicles. Although only one EV is triggering network updates, this is enough to create a slight bottleneck effect that affects network performance. In fact, although the network creation time seems quite short compared to other values, it still takes more than 1s. We also ended up with a message redirection time of about 6s to contact about 70 vehicles. This is primarily due to the sum of several factors: the time spent to handle the first message, the overhead involved in the delivery to the controller, the processing time, and the update time of the network configuration. These different values could be improved by using other controllers to alleviate the network load, and by optimizing the application-layer software developed.

VI. Conclusions and Future Work

As ITS services and underlying technologies continue to expand, novel solutions can be envisioned that go well beyond current state of the art, achieving improved performance in unforeseen ways. In this paper we have presented such a solution by leveraging on the potential of VANET and SDN technologies. In particular, we have devised a strategy that allows emergency vehicles to improve their travel times in congested urban environments by requesting those vehicles occupying the lane they intend to use in a near future to free that lane. This is made possible by a combination of elements including: (i) VANET-enabled vehicles and EVs, (ii) an SDN-based infrastructure that includes RSUs along the city, and (iii) a sophisticated application that is aware of RSU deployment, and that can interpret EV messages, so as to select the adequate geographic locations for message dissemination; such approach allows reaching all required vehicles along the EV's path (for its near future locations), while minimizing the amount of radio resources consumed.

Our proposed solution as been formally presented in this paper, and evaluated through simulation by combining both Mininet and SUMO tools. Experimental results for a realistic setting in the city of Valencia, Spain, have shown that we are able to improve the travel time of EVs by nearly 15% when requesting vehicles occupying the lane used by the EV to move aside for a specified period τ; experimentally we have shown that a period of 50s achieves the best results in terms of reducing the EV travel time, while maintaining the the time penalty experienced by other drivers at negligible levels.

As future work we plan to extend our solution, which currently relies on message exchange via RSUs only, to also support direct communication between the EV and other vehicles so as to free the lane reservation made as soon as the EV passes by. Such approach is particularly applicable to autonomous vehicles, as regular drivers are well aware that the EV has passed. We also plan to extend our study to other city profiles, characterized by a different number of lanes and different traffic loads, to assess the gains achieved by our solution under different settings.

Acknowledgment

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