Cognitive Cars: Constructing a Cognitive Playground for VANET Research Testbeds

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ABSTRACT

Simulation today plays a key role in the study and understanding of extremely complex systems, which range from transportation networks to virus spread, and include large-scale vehicular ad hoc networks (VANETs). Regarding VANET scenarios, until very recently, simulation has represented the only tool with which it was possible to estimate and compare the performances of different communication protocols. In fact, it was not possible to thoroughly test on the road any VANET-based multi-hop communication system, as no highly dense vehicular testbed exists to this date. This situation has recently changed, with the introduction of a new *COGNITIVE* approach to VANET systems research, where it has been shown that it is possible to perform realistic experiments using only a few real vehicular resources (i.e., only a few vehicles that are equipped with wireless communication interfaces). Now, the scope of this paper is to show that it is possible to move further ahead along this recently drawn path, utilizing the features provided by cognitive network technologies. In particular, we will show that cognitive interfaces can play a role as an additional tunable dimension to be used within an experimental platform where highly dense vehicular testbeds can be structured, even in the presence of a few real vehicular resources. The advantage is twofold: (a) they can be used to test new strategies for dealing with the scarcity of spectrum in a very dynamic environment as the vehicular one is, and, (b) they can be used to test the performances of VANET protocols as a function of different frequencies and interface switching delays. As an example of how this can be done, we will provide preliminary results from a set of experiments that have been performed with a highway accident warning system and with a cognitive network based on the Microsoft Software Radio (SORA) technology.

Categories and Subject Descriptors

D.3.3 [**Performance of Systems**]: *design studies, measurement techniques, modeling techniques.*

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General Terms

Measurement, Performance, Design, Experimentation.

Keywords

VANET Testbeds; Experiments; Vehicular Overlay Networks; Software Radios; SORA Networks; Cognitive Networks.

1. INTRODUCTION

Vehicular ad hoc networks (VANETs) keep being one of the missing pieces of the systems and networking research puzzle, as almost all the research efforts that have been carried out in this field are based on computer simulations. Although the modeling detail that can be reached with simulations keeps improving (thanks to a steadily increasing computing power), all the research that concerns devising and building VANET testbeds remains limited by the number of vehicles that can be equipped, at a reasonable cost, with communication technologies.

Despite the lack of realistic testbeds and the barrier that this has represented in vehicular ad hoc network research, the scientific community has been relentlessly devising new communication protocols for VANETs. In fact, communicating cars could support a number of new innovative applications, ranging from community-oriented programs such as pollution control on streets, to entertainment such as online gaming. But this is only part of the story, considering that connected platoons of vehicles could provide a dynamic communication infrastructure, in addition to those that are already in place (e.g., phone, Internet and cellular networks), with the further advantage of being resistant to all those events that are capable of shutting down the electric grid (e.g., earthquakes, tornados, terrorist attacks, etc.). In essence, vehicular networks research remains a hot topic despite the lack of convincing experimental results in effective deployments. This fact is also witnessed by the attention that any practical advancement in this field receives by the general public and mass media (e.g., [1]).

Now, it has been very recently shown that with *Cognitive Cars* it is possible to perform real experiments with VANET applications and communication protocols while successfully dealing with the limitations provided by vehicular and computing resources [1], [2]. In particular, the authors of [2] have devised the guidelines that should be followed to reconstruct the situation that a communication protocol would experience on a street while running on a VANET, as a function of three physical variables (the number of hops traversed by communication packets, vehicle density, channel conditions). All this has been shown to be possible by recreating the conditions (hops, vehicular density and channel conditions) that a communication packet would encounter on an arbitrary long path between two vehicles, by simply utilizing a few vehicles that emulate those conditions.

Now, borrowing a few of the ideas that are at the basis of cognitive network technologies, we will here show that it is possible to extend the ideas that have been presented in [2], to further increase the flexibility of realistic experiments with VANETs, while using a limited amount of vehicular and computational resources. In fact, one of the most interesting features of cognitive networks is their possibility to dynamically tune network parameters (e.g., frequency, power, etc.) to optimize end-to-end performance. Cognitive networks, hence, represent a technology that can increase the efficiency of network performances, but can also be employed as a tool that enables the understanding of how network performance varies while tuning the network parameters, for changing system conditions.

In essence, cognitive interfaces play the role of an additional tunable dimension to be used within the framework introduced in [2], where highly dense vehicular testbeds can be structured, even in the presence of a few real vehicular resources. Thus, cognitive networks can play two different, but equally interesting, roles. The first role is that of increasing the overall throughput experienced in a very tough environment, such as the vehicular one. In fact, in the near future, when all vehicles will be equipped with communication interfaces that comply with dedicated short-range communications (DSRCs) standard, the radio spectrum reserved for vehicular transmissions may become scarce. Moreover, as the DSRC standard is not universally accepted (it is accepted only in the EU, US and Japan), transmitting on the 5.9 Ghz frequency may be illegal in many countries. Then, for one reason or another, vehicular applications may be forced to switch to share the unlicensed frequency bands with residential users, in order to achieve acceptable performances. The second, but not less interesting role that cognitive networks can play is that of increasing the number of variables that can be tuned when testing vehicular communication protocols. In particular, cognitive radios offer the capability, termed dynamic spectrum access (DSA), of dynamically accessing the available spectrum. Hence, it is possible to utilize the DSA capabilities of cognitive radios to test the performance of a communication protocol as a function of: (a) the utilized channel frequency, and, (b) the frequency switching speed.

Although this paper will mainly present the architecture guidelines that should be adopted to implement a vehicular testbed that can be employed to perform more than a very limited set of experiments (termed hereafter *cognitive cars* in our paper) we will also provide practical results drawn from our tests on: (a) an accident warning system implemented for highways, and, (b) a cognitive network based on the Software Radio (SORA) technology provided by Microsoft.

This paper is organized as follows. In Section II we summarize some of the most relevant contributions that have so far been presented in the domain of testbed systems for vehicular networks. In Section III we present the contribution of this paper, while Section IV describe our experiments. We finally conclude with Section V.

2. RELATED WORK

The works that have so far devised and studied the performances of communication protocols on vehicular networks using popular simulation platforms are many and difficult to enumerate. Here, we will focus on those few research initiatives that, instead, did not limit their studies to theoretical and simulative analysis, but also published results drawn from real tests performed on vehicular testbeds.

Leontiadis et al. developed a vehicular testbed experiment focused on assessing: (a) the throughput that can be achieved between two moving vehicles, and, (b) the time required by a simple gossip protocol to disseminate mobility information within a vehicular testbed composed of eight cars [3]. Compared to our approach, the experiments that are reported in this paper are limited in their depth in a number of ways. This study, for example, does not analyze how the achieved throughput of the proposed gossip protocol varies as the number of hops between two different vehicles changes. The performance variations that are due to networking variables such as interfering vehicles, varying channel conditions and the use of different frequency bands, when communicating between two vehicles, are as well ignored. Hence, although this paper presents a few interesting performance figures, a more systematic experimentation campaign is needed to confirm the results that are presented in terms of bandwidth consumption and delivery delay.

The work that has been presented by Amoroso et al. in [2] is at the basis of the proposal that is formulated in this paper. The authors, in fact, show that it is possible to perform sound vehicular experiments that would require the use of many cars with only a few vehicles, while resembling, as closely as possible, the situation that would be experienced in reality. In brief, they propose the creation of a virtual overlay network, composed of relaying and interfering vehicles, on top of a platoon made of only a few vehicles. Such overlay network supports the implementation of experiments where communication packets can travel for an arbitrary number of hops, while experiencing the interference of an arbitrary number of vehicular transmitters as the physical channel characteristics vary. Compared to the cited piece of work, we here propose a further step forward: the use of cognitive radios to investigate how different frequency bands and different frequency switching times can affect the performance of communication protocols in challenging vehicular environments.

Summarizing, with the sole exception of the tests that have been presented in [2], the experimental work that has so far been published in literature is generally limited by the use of a restricted vehicular infrastructure [3]-[8]. In fact, all research groups, in different ways, have encountered the common problem of having only a limited number of resources (i.e., vehicles and drivers) available. Hence, we believe this is the first *Cognitive testbed* proposal that, at once, permits a communication protocol designer to confront with five different dimensions (Figure 1):

- N = number of hops,
- $D(v)$ = density of interfering neighbors,
- $C(t, s)$ = wireless channel conditions,
- $F(n)$ = transmission frequency at node n,
- $d(n)$ = switching delay at node n.

3. THE *COGNITIVE CARS* TESTBED

Similarly to [2], the idea at the basis of the cognitive car testbed is that of implementing a unicast branch of a multi-hop path in place between a given sender and a given receiver. What, instead, differentiates this work from [2] is that, when testing the performance of a communication protocol, we can now tune two additional variables, the frequency band utilized for transmitting and receiving communication packets as well as the switching time required to change from one frequency to another. However, before moving on to how cognitive radios can be used for such scope, we will first briefly describe the architecture of the vehicular testbed that has been presented in [2].

3.1 Varying Interferences, Hops and Channels

To this aim, we will first define a few variables that will be helpful to decipher the diagrams shown in Figure 2. With S we indicate the vehicle that acts as the source of communication packets, while with D the final destination vehicle. The relays that retransmit data packets between S and D are denominated as R_i. T_i indicates a single transmission event, among those that are necessary to transfer data packets between S to D. As an example, if D can hear the transmissions of S directly, such situation entails that only a single transmission (i.e, T_1) may be required to transfer one unit of information from S to D. I_j, instead, is the j-th interferer (i.e., the j-th vehicle that, transmitting units of information, disturbs the communication between S to D).

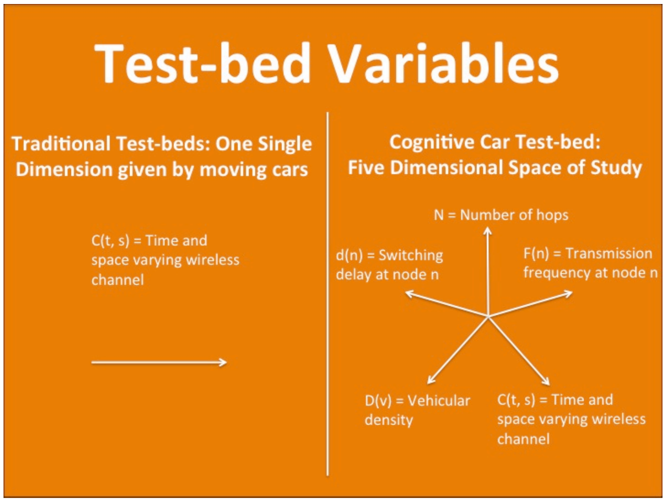

Figure 1. Testbed approaches: traditional vs. cognitive ones.

Now, the vehicles that have been so far defined (S, D and the R_i vehicles) are all *virtual vehicles* and need to be logically mapped into a real infrastructure. In the Cognitive Car Testbed this is made possible by the creation of multiple virtual machines in the Car Router. An example of how this can be done is shown in the top-left diagram of Figure 2, where eleven different virtual vehicles are mapped into three real vehicles. This process entails mapping each virtual vehicle into one of the available real vehicles, while following two rules of thumb: (a) vehicles that share the channel in the same contention area in the virtual case should be mapped into vehicles for which the same situation holds in the real case, and, (b) the link length proportionality observed in the virtual case should be roughly reproduced in the real one. Again resorting to the top-left diagram drawn in Figure 2, we can observe, for example, that R_3, which has been mapped in the leftmost vehicle, can hear in reality its virtual neighbors: R_2, I_3 and R_4.

Once all virtual vehicles have assigned to different virtual machines in different real vehicles, the next step is mapping virtual into real hops. Such operation naturally follows from the preceding one, as all the virtual vehicles that intervened between the source and the destination vehicle were already known. Virtual transmissions T_1 through T_7 are implemented by the real hops that are traversed by any communication packet that is sent between S and D in the right-most part of Figure 2.

A further variable of interest, when experimenting with VANETs, is the channel condition. In fact, as the three vehicles represented in Figure 2 move, they will encounter radically different scenarios, ranging from highways to rural roads, from desert areas to densely populated ones. As the vehicles that compose the testbed move, hence, they are able to perform the same experiment again and again, experiencing each time different channel conditions. For this reason we periodically repeat the same given experiment every Δt seconds, as shown in the bottom part of Figure 2.

3.2 Frequency Hopping and Switching Delays

Within the framework of interest, two very interesting performance variables are given by: (a) transmission frequency bands, and, (b) frequency switching times.

In fact, for the reasons that have been explained in the introductory section, it may be convenient for a vehicular application use the same radio resources that are generally occupied by residential customers, momentarily leaving the ones reserved for vehicular communications. Such scenario might present, for example, when an efficient transmission of a critical piece of information (e.g., an alert message in a highway scenario) requires a timely adaptation to the spectrum conditions that are faced by that vehicle. Clearly, the choice of switching from one frequency band to another, within a vehicle, comes at a cost (i.e., delay), and this factor should be accounted for when taking such type of decision.

How our testbed technology can benefit from the use of cognitive radios is very simple to describe and is briefly depicted in Figure 3. In fact, while a platoon of vehicles advances, a virtual vehicle running on one of the real vehicles can decide to switch to use another frequency for its transmissions. $F(t, s, n)$, in fact, is the function that represents the frequency adopted by the n-th vehicle, at time t, in position s. With $d(t, s, n)$, instead, we represent the delay that is incurred at node n, when a switching decision is taken. Hence, while an experiment is running, it is possible to hop back and forth from one frequency to another, as communication packets advance along their path.

4. *COGNITIVE CARS* AS A STUDY TOOL

The applications of the technique that we here present are numerous, and not limited to the ones that we will here discuss. To give however an initial idea, we will sketch a few applications where a cognitive car testbed, as the one that we have briefly described, can be utilized.

A first natural application is that of studying the performance of cognitive networks, without carrying the heavy burden of being limited by the constraints imposed by traditional testbeds. In fact, using the testbed technology presented in this paper, it is possible to observe the throughput and the delay experienced by communication packets, regardless of the number of hops that they traverse, of the number of interfering transmitters they hear and of the channel conditions that they face. However, our cognitive car testbed can be also employed to devise other type of tests that aim at assessing the transmission of packets between moving vehicles, while experiencing radically different propagation situations on the road. In fact, a cognitive car can be a useful tool to measure the performances obtained using different frequencies, while traversing heterogeneous environments.

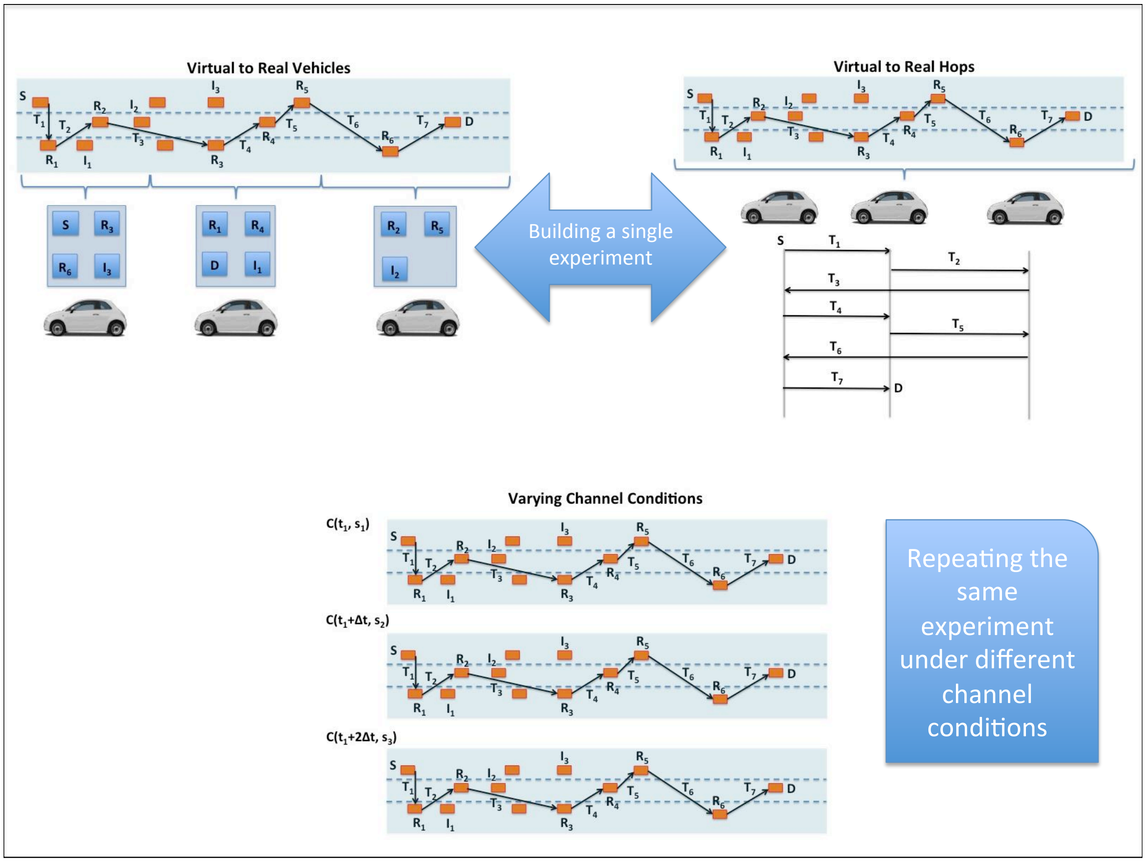

Figure 2. Building a cognitive car testbed: initial steps.

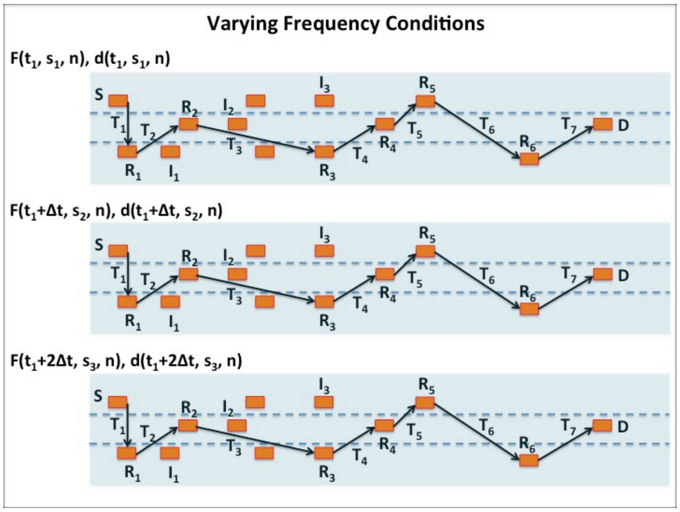

Figure 3. Varying the frequency use.

The optimal frequency band that should be used during a transmission round is a function of not only the number of interfering vehicles, but also of other conditions such as the meteorological situation, any near obstacles and the speed of moving vehicles.

Hence, a cognitive car testbed can be used to verify how different interface technologies perform and how transmissions are affected by different frequencies.

Concluding, such type of technology well applies to those situations where bulk transfers occur between two vehicles, a source and destination, following a multi-hop path and where the adopted frequency (as well as the adopted modulation scheme) can heavily affect the performances that are experienced along the path. Now, to turns words into action, we will here provide two practical examples of how this methodology can be applied, as well as a set of preliminary results.

5. EXPERIMENTS

We performed two sets of distinct experiments. Within the first set of experiments, we aimed at confirming the general principles that are at the basis of cognitive cars: the ability to perform multi-hop communications on a real testbed, with limited resources. To do so, we tested an accident warning system with only four cars driven on Los Angeles highways [2]. While the vehicles were moving, they traversed radically different situations that ranged from highly dense urban areas to desert areas, where seldom any other car could be crossed.

In particular, during this experiment we aimed at measuring how far and with what delay an alert message could propagate utilizing a platoon of moving vehicles. Clearly, the vehicles of the platoon moved following traffic rules and their respective distances varied as traffic conditions changed, consequently communication faults could be caused by a number of physical causes, including an absence of connectivity due to an excessive distance between two subsequent vehicles of the platoon. Each single experiment began with the first vehicle of the platoon sending an alert message and the other vehicles retransmitting it, following the protocol proposed in [9]. This is a typical experiment scenario where there is no desire to limit the number of hops between a source and a destination vehicles, as the number of hops that are traversed represent a performance figure of the experiment.

We here only sketch a few of the preliminary results obtained during one of our experiments. During the considered experiment, 140 alert messages have been broadcasted, hence, they experienced, while travelling, 140 radically different channel conditions. The average numbers of hops travelled by each of these messages slightly exceeded 12, while each alert message on average travelled for a distance of 1.1 km. Interestingly, although we utilized high gain antennas which irradiated 25 dBm of power while operating within the 2.4 Ghz unlicensed band, the distance travelled during a single hop by a communication packet rarely exceeded 100 m, witnessing that vehicular environments represent a tough test case for any communication protocol.

The second set of experiments was performed in the lab utilizing two Microsoft SORAs, programmed to be able to switch between WiFi channel 3 and WiFi channel 9. With this experiment we aimed at assessing one of the two innovative dimensions of the cognitive car testbed: the switching time required between two different frequency bands. Performing a couple of experiments in both static and walking situations, we observed that switching times ranged between 1.6 and 2.4 ms. Now, putting such results into the context of the first experiment, we can deduce that an accident warning system that propagates accident information through a vehicular network based on cognitive networks might experience an additional overhead time of 2 ms, on average, per vehicle. Considering the specific case given by our experiments, where we covered an average distance of 1.1 km with each transmitted packet, we have that on average an alert message would have experienced an additional delay of 24 ms, given by multiplying the average number of hops traversed by a single alert message for the average switching delay.

Clearly, although all these final considerations do not require any particular analysis capabilities, it is important to remind that they have been possible only thanks to a set of realistic experiments that have been run on the roads of Los Angeles. Hence, while the results that can be drawn by advanced communication interfaces, as cognitive radios, are key to reach any type of result, a wise devise of testbed experiments can lead to the observation of performance figures that otherwise would not be observable in reality.

Concluding, cognitive cars can be an enabling technology for many studies and analysis that otherwise would not be possible.

6. CONCLUSION

This paper showed how it is possible to utilize the features provided by cognitive network technologies within the domain of advanced vehicular testbeds. We showed, in particular, that cognitive interfaces can: (a) be used to test new strategies that deal with the scarcity of the radio spectrum in a vehicular environment, and, (b) be utilized to assess VANET protocol performances as a function of different variables. As an example of how this could be done, we provided preliminary experimental results obtained from a highway accident warning system and a cognitive network based on SORA interfaces.

7. ACKNOWLEDGEMENTS

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