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1. Final publishable summary report

Communication-enabled vehicles are on the verge of large-scale deployment. On the one hand, automotive services are one of the main use cases considered in the design of 5G architectures that will start replacing the current cellular technologies in 2020; on the other hand, dedicated short range communication (DSRC) is ongoing field tests and may be enforced as a standard technology in new vehicles by regulators within 2018. The 5G and DSRC approaches are somehow in competition, but have complementary strengths: no clear winner has thus emerged, and carmakers are prone to implement both solutions in their connected vehicles.

A common feature of the 5G and DSRC architectures is the central role of direct communications among vehicles, in the form of infrastructure-driven device-to-device (D2D) or spontaneous vehicle-to-vehicle (V2V) transfers, respectively. Direct communications will enable substantial applications, e.g., road safety functions that require ultra-low latency to broadcast danger warnings to nearby vehicles, or massively crowd-sourced urban sensing based on floating car data. More generally, direct vehicular communications will help relieving the infrastructure from part of its load.

The forthcoming availability of D2D/V2V communication technologies and the relevance of the novel services that they will support advocate that we fully understand the capabilities of this new networking milieu. The ReFleX project targeted precisely that aspect, by investigating the (still largely unknown) fundamental topological and connectivity properties of large-scale networks formed by networked vehicles, so as to lay the foundations for the design and evaluation of effective vehicular network solutions.

To achieve its objective, the ReFleX project set forth the following key contributions.

First, the ReFleX project generated a number of novel datasets of vehicular mobility that are specifically developed for use with networking simulators. The datasets generated within the project cover both highway and urban environments, and are based on high-detail traffic count measurements, realistic origin-destination (O-D) matrices, and GPS logs of actual vehicles, all of which faithfully describe the vehicular travel demands observed in real-world road traffic scenarios. The generation processes leveraged and enhanced state-of-the-art tools for the simulation of microscopic vehicular mobility, and involved solving challenges in the integration of realistic data sources and mobility simulators. The datasets produced by ReFleX contribute to the current state-of-the-art in highway and urban road traffic for network simulation.

Second, the ReFleX project collected a large number of datasets of vehicular mobility that are compatible with the requirements of network simulation, and built a first-of-its kind repository of road traffic data for network simulation, as part of the official project website. The repository provides direct open access to all such datasets, including those generated within ReFleX itself; as such, it has a high potential to foster dependability, reproducibility and verifiability of research on networked vehicles and their supported services.

Third, ReFleX developed enhanced propagation models of the radio-frequency signals that enable D2D/V2V communication. These novel models build on stochastic representations that account for the shadowing induced by buildings and surrounding vehicles on the propagation. They have the significant advantage of being highly efficient from a computational viewpoint, which allows using them in large-scale simulations of networked vehicles.

Fourth, ReFleX proposed original approaches to model the vehicular network connectivity arising from the two most popular communication paradigms employed in vehicular networking: (1) connected forwarding, where data is transferred instantaneously from source to destination, exploiting a fully connected multi-hop path of D2D/V2V links; and (2) store-carry-and-forward, where data tolerates latency and can thus be physically carried by one or more vehicles for some time before it is handed over to the destination. The models developed in ReFleX built on tools from complex network science and evolving temporal graphs, and allow for an efficient representation of large-scale scenarios where tens of thousands of vehicles are concurrently present. An in-depth investigation of the models in presence of realistic mobility datasets revealed original properties of vehicular network topologies in urban and highway environments that were previously unknown or misunderstood. These include: (i) the extremely poor network-wide connectivity granted by connected forwarding in both highway and urban settings; (ii) the limited availability, stability and navigability of vehicular networks under the same transfer paradigm; (iii) the strong dependence of connected forwarding topology on two simple factors, i.e., the communication range and the road traffic density; (iv) the significant (between two and three orders of magnitude) improvement in connectivity granted by store-carry-and-forward with order-of-minute latencies; (v) the possibility of anticipating key topological features of a vehicular network based on store-carry-and-forward by knowing trivial macroscopic features of the urban area of interest.

Fifth, the ReFleX project leveraged the unique combination of realistic mobility datasets and understanding of the topological features of vehicular networks in order to provide insights into multiple relevant applications. Namely, ReFleX studied: (i) the collection of sensing data from networked vehicles via so-called floating car data (FCD), by exposing the important scenario factors that influence the quality of the sensing process, and by devising near-optimal protocols for the management of FCD upload; (ii) the diffusion of malware in vehicular networks via D2D/V2V communications, by identifying the substantial risk the such technologies pose in terms of security, and by proposing effective smart patching measures; (iii) the interplay between networked vehicles and the existing cellular infrastructure, by revealing substantial limitations of the current LTE technology in supporting automotive connectivity, and by identifying recurrent patterns that are useful to the design of more appropriate radio access deployments.

The results achieved by the ReFleX project have significant potential for scientific impact. The dataset repository built and maintained by ReFleX can play an important role in fostering the (currently poor) reliability, reproducibility and verifiability of research results in the vehicular networking field. The solutions devised by ReFleX for the generation of vehicular mobility datasets can be applied to any road traffic generation process, and thus ease the work of other research groups. The analyses carried our by the ReFleX project on the fundamental topological properties of networks of connected vehicles provide substantial new knowledge that is extremely useful for deriving guidelines towards the design of effective protocols and algorithms for vehicular networks. In addition, the results of ReFleX were disseminated at large, through publications appeared in top-tier journals and conferences in computer science, as well as talks, seminars and lectures at national and international venues.

Project website: http://www.wcsg.ieiit.cnr.it/Reflex/website/#datasets.
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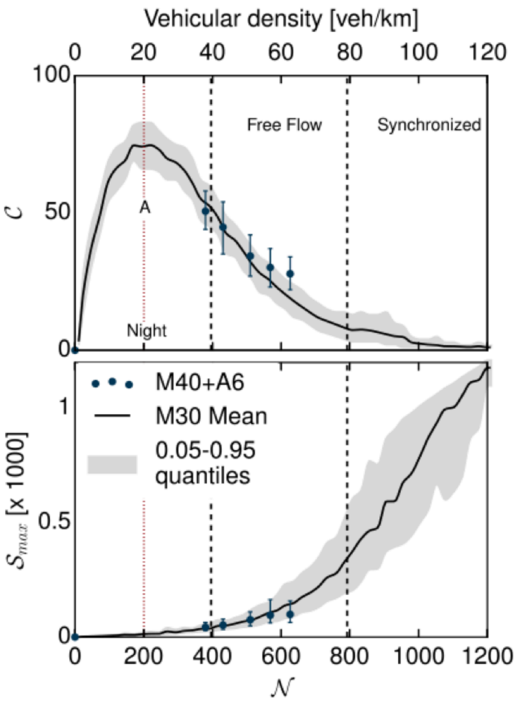
<u>Attached documents</u>

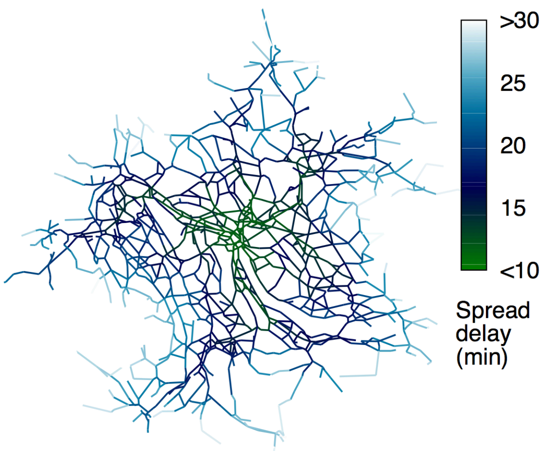
1. Project logo

2. Vehicle trajectories (red) and buildings (grey) in three sample scenarios generated within the ReFleX project by calibrating real-world GPS data and crawling open map databases.



3. Connectivity of a vehicular network in highway environments. The top plot shows the number of components (lower indicates a better connectivity, 1 means that the network is fully connected and all vehicles can potentially communicate with each other) versus the road traffic intensity (expressed as the number of vehicles per km on the top x axis). The bottom plot shows the number of vehicles in the largest component (higher indicates a better connectivity) versus the road traffic intensity. The characteristic bell-shaped function describes the three phases of connectivity: (1) all vehicles are disconnected before the “A” threshold; (2) vehicles form increasingly larger components beyond the “A” threshold; and (3) vehicles form a single fully connected component at the very right of the plots.

4. Automotive malware epidemics via D2V/V2V communications in the Canton of Zurich, a 10,000-km^2 region in Switzerland. The color associated to each road segment denotes the time needed to infect 95% of the vehicles in the whole region, when the epidemic originates at such road.



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