Towards Vehicular Fog Computing: an Architecture for Connected Vehicles and Vehicular Clouds

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***Abstract*—Amazing progress of various inter-related technologies, such as communications, automatic control, and embedded systems has changed the traditional vehicle model pushing it forward towards new paradigms: Internet of Vehicles, Connected Vehicles, Vehicular Clouds/Fogs, Fog Computing, Smart Vehicles, Intelligent IoV etc. However, implementing such paradigms is very challenging due to their extreme complexity, which prevents them to be a more substantial part of our daily life, at the full potential of the technology involved. To tackle such complexity, new approaches are necessary and, therefore, we propose here a user-centric architecture of a smart connected vehicle that can be used also for smart surrounding environments and that provides for autonomic, pervasive, and fog computing. Its current implementation in a connected vehicle is also shown.**

Keywords—smart autonomic connected vehicle, vehicular networks, vehicular clouds, vehicular fog computing

I. INTRODUCTION

Smart environments of the future can be seen as small worlds that fully embody Mark Weiser and many others' vision of ubiquitous and pervasive ambient intelligence, taking a myriad of physical forms and able to serve and support people continuously, in their daily life. All that intelligence works transparently and unobtrusively, yet pervasively, around people and together with them, to improve their experiences, their comfort, and, finally, their quality of life, leading to a paradigm shift in the way our society works and exists [1, 2, 3]. The people are at the very core of this emerging scientific, technical, and cultural phenomenon that includes a crowd of interacting smart environments, which are expected to be highly adaptable, increasingly autonomous, and more and more able to communicate naturally with humans. In such a smart world, an infinity of use scenarios may unfold, e.g., let us imagine a family that is very interested in old wooden constructions, and, while being in vacation, it drives through a little crossroad, unaware that 10 miles away a very interesting medieval wooden church is finally open and they get that particular piece of information from a road side unit that has "retained" it from a vehicle that has passed by earlier. A vision within a vision emerges, no matter how we call it: Internet of Vehicles (IoV), Vehicular Cloud/Fog, Intelligent Vehicle Grid, Smart Autonomous Environment, intelligent Internet of Things, etc. Scaling this scenario, we have millions of intelligent vehicles connected to each other, to the smart surrounding environments, and to the Internet, which exchange information and knowledge with their peers, the people, and the intelligent autonomous vehicle grid or, generally, with the IoT [4]. Making this vision a reality is still very difficult, mainly because of the inherent complexity of implementing it seamlessly in our daily life, at a large scale.

To tackle such complexity new approaches are essential and, therefore, we propose here *a user-centric architecture adaptable to both smart connected vehicles and smart surrounding environments*. Despite this particularization, *this architecture is general and can be used for any smart spaces and their surrounding smart environments*. Human users have an active role within this user-centric architecture, being able to either explicitly ask for services from the smart connected vehicles and environments and/or to get support automatically when "they see" she needs help. This provides for a more powerful vision of people who get recognized and responded individually, in an "invisible way", by intuitive intelligence embedded in everyday objects [2]. More, he can get to experience new things or situations that may even influence his behavior for the better (e.g. for driving safer). The main contributions of this work are (1) a comprehensive architecture that provides for autonomic, pervasive, and fog computing, which is both adaptable and general, and (2) its preliminary validation through implementation in a real world system. The architectures in the related work are either implemented just as working prototypes to validate a particular approach, or evaluated by simulations or discussions. Our current architecture has been in place only for the last few years of the 15 years the system is in operation (on more than 500 cars), because it has proved to be the most appropriate to tackle the major technology changes, growing system complexity, enhanced functionality, increased refinement of user needs, and the agile development process. Compared with the related work, the architecture we propose is the most elaborated and can be used both for smart connected vehicles and smart surrounding environments.

The next section illustrates the challenges of building smart connected vehicles working together within smart environments. Section 3 includes the related work, while our architecture and its implementation within a smart connected vehicle are shown in Section 4. The final section includes conclusions and future work.

II. SMART CONNECTED VECHICLES AND VEHICULAR NETWORKS

Today vehicles are a swarm of sensors, devices, actuators (effectors), and specific computing that aim to get us to our destination with maximum safety and comfort, and with minimum costs and impact on the environment. They accomplish their tasks increasingly based on their “prosumer” capabilities, i.e. on their increased ability to “absorb” information from some entities in the environments and to “feed” it further to other entities (drivers, infrastructure, data, information and knowledge sources, fleet managers, etc.) that are involved in safe navigation, pollution control, traffic management, and so on. This allows them to make intelligent knowledge-based decisions that provide for, ultimately, a more sustainable way of life [4, 5]. Thus, *smart connected vehicles* can exist only intrinsically connected with their *smart surrounding environments*, as a powerful unified universe, in which a huge variety of “Things” exist and evolve, from the simplest ones (smart sensors and devices) to the very complex ones (e.g. pervasive or fog computing environments) (Fig. 1).

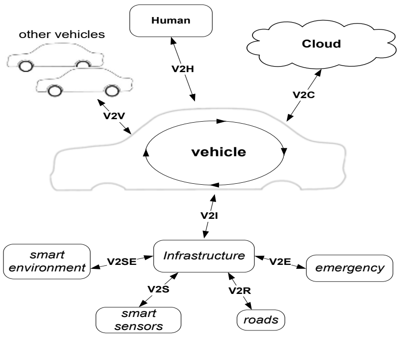
Fig. 1. Connected vehicles in a smart environment

An ad-hoc virtual network can be created for collaborations among network members (vehicles) to produce evolved vehicular services that individual vehicles alone cannot provide. Thus, vehicles in the vicinity can opportunistically form a local group (*a vehicular fog*) for cooperative computing in which *vehicle contents and services are produced, maintained, and consumed* [6]. The vehicular fog has the potential to be the core system environment that makes this evolution possible [5].

Within smart environments, vehicles can communicate with each other via a variety of available communication channels (Fig. 2). There is also communication inside the vehicle. Communication issues are challenging due to the variety of heterogeneous devices involved, the diversity of the technologies used, the highly dynamic environment, the environmental noise, and so on. The main functionality of a smart autonomic connected vehicle is shown in Fig. 3.

Scenarios in which the user can benefit from the available services even when there is no Internet available (e.g., no data coverage or no Internet subscription) need to be possible as well. He can still interact with the other vehicles, the roads’ infrastructure, and the local smart environments.

A variety of available sensors and devices (such as road condition sensors, vehicle distance sensors, forward/side/rear obstacle sensors, blind spot and rear view monitoring cameras, drive recorder, air pressure sensor, GPS sensor, airbag, electronic control brake and steering, etc.) provides for functionality that has not been imagined for the first motorized vehicles. All those provide for creating truly smart vehicular networks in which connected vehicles work together to offer their users a large variety of services [4-8]. However, the development is difficult due to several specific constraints:



V2H: vehicle to human user, inside and outside vehicle
V2V: vehicle to vehicle
V2C: vehicle to Internet clouds
V2S: vehicle to smart sensors
V2R: vehicle to road infrastructure/RSU - Road Side Units
V2E: vehicle to emergency services (eCall included), manual or automatic
V2I: vehicle to infrastructure
V2SE: vehicle to smart environment

Fig. 2. Vehicle communication within a smart environment

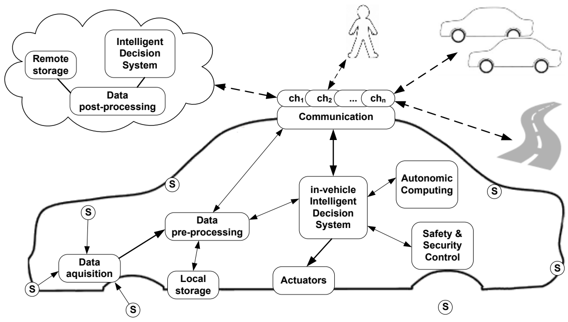


Fig. 3. Smart autonomic connected vehicle

- vehicles operate in highly mobile environments, moving from place to place, often at high speeds, so data connection can be lost (areas with poor coverage);
- the driver should benefit from them, without diverting his attention from driving, so the interaction with him is unlike in other smart spaces (home, office, etc.);
- they have to provide for safety, at all times, for all users (driver, passengers, pedestrians etc.) and that is hard to achieve since the vehicle is very limited and includes a high number of mechanical and electronic devices and sensors that perform complex tasks;
- the control of the vehicle has to be smartly assigned to the most appropriate “One” for the job, at any given time, e.g. if the driver becomes unable to drive, an autonomous vehicle can take over and do it itself;
- human activities are highly constrained by the confined vehicle space and only reduced activity options are available both for passengers and the driver (by what she can do while driving a non autonomous vehicle);
- tackling several issues resulted from use of various sources of federated data, information, and knowledge due to the huge dynamics of the environment;
- need for very low power consumption when engine is not running to avoid the “flat battery” syndrome;

- high reliability of on-board hardware and software, as automotive devices are notorious for extreme operation conditions (large temperature range, different shock levels due to sudden acceleration or extreme breaking, constant vehicle vibrations and, implicitly, of sensors and devices). More, they are expected to work for the entire vehicle lifetime (5 to more than 10 years);
- the architecture of such spaces has to be highly extensible, easy to update for integrating new protocols and technologies, standardization being mandatory;
- automotive computing consists of a number of highly specialized Electronic Computing Units. In an average car, tens are available and perform different tasks: engine control, transmission control, active safety (e.g. ABS brake control, ESP stability control), driver assistance (automatic parking), passenger comfort (central locking), and passenger entertainment. These are parts of a distributed system and can communicate with each other usually by one or more interconnection buses (Control Area Network - CAN). Because each ECU is specialized in doing a very specific task, they cannot perform other kind of computations, so, for now, it is impossible to consider them general purpose computing units to be used, e.g., for number crunching.

III. RELATED WORK

The amazing progress of various inter-related technologies, such us communications, automatic control, and embedded systems has changed the traditional vehicle model pushing it forward towards the Internet of Vehicles, which, as *an instantiation of the Internet of Things*, is expected to have communications, storage, intelligence, and learning capabilities able of anticipating users' intentions [5]. This transition will be facilitated by the Vehicular Cloud, considered the equivalent of Internet cloud for vehicles and expected to provide all the necessary services for the autonomous vehicles [4-8]. Vehicular clouds, as the *next paradigm shift for vehicular networks*, provide for unutilized storage, computational, and communication resources inside vehicles to become nodes in cloud computing [7]. Various scenarios are envisaged, e.g. the on-board resources of vehicles stuck in traffic could be used to run complex simulations aiming at alleviating the traffic jams by the traffic management centers. Moreover, the authors postulate that autonomy and self-organization of vehicles into clouds will naturally follow. They have coined the term *Vehicular Cloud (VC)* to refer to a group of largely autonomous vehicles whose corporate computing, sensing, communication, and physical resources can be coordinated and dynamically allocated to authorized users. Novel types of services are foreseen, such as *network as a service, storage as a service, and cooperation as a service*. Various possible applications are considered, i.e. airport (or mall) data centers, parking lot data clouds, special event management, dynamic synchronization of traffic lights, dynamic traffic signal optimization, dynamic assignment of high occupancy vehicle lanes, evacuation management, autonomous mitigation of recurrent congestions, sharing on-road safety messages, dynamic management of parking facilities, homeland securities applications and vehicular clouds in developing countries etc. Two types of architectures are shown, one static (e.g. a cloud of vehicles in a company's parking lot) and one dynamic (based on ad-hoc vehicular clouds formed to, e.g., dynamic traffic event mitigation) [7]. A survey on Vehicular Cloud Computing (VCC) put emphasis on the opportunities provided by merging mobile cloud computing and vehicular networks [9]. Moreover, it extends the cloud services shown in [7] to include information and entertainment. They propose a VCC architecture that includes the inside vehicle's space, the communication layer, and the layer of services and applications offered by the cloud.

Vehicles are seen as *a phenomenal computing resource in terms of storage and processing* also in [9], but the author considers that the real power of the vehicle computing cloud is based on the sensors they carry. Two significant capabilities, *collecting large amounts of sensor information* and *the local relevance of this information*, represent the key advantage of the Vehicle Cloud over the Internet Cloud (a point of view that we share). Moreover, storing and processing as much as possible of this information on the vehicle results in major savings (e.g. cost and time of uploading and downloading).

An interesting discussion on the characteristics observed in emerging vehicle applications and some consequent guidelines for development is in [4]. Thus, the application content-space validity requires that the data should be kept on the vehicles rather than being uploaded to the Internet, which will provide for both enormous spectrum savings and scalability of the autonomous vehicle concept, given the massive quantity of data collected by vehicle sensors. More, content centric networking will be the backbone of management and control of autonomous car fleets. Collaboration in sharing and processing sensor data is anticipated to be one of the key assets of smart autonomous vehicles. Intelligent Vehicle Grid is defined as an intelligent road infrastructure similar to the energy grid, composed by various Things such as vehicles' sensors, RSUs, RFID tags, and embedded microcontrollers.

An architecture of a smart in-vehicle space built on top of the ScudWare middleware is presented in [10]. It includes components for monitoring (traffic, driver, car), risk assessment, driver warming, and car actuator, and models of both multitasking driver cognitive behavior and context, based on ontologies (driver, car, and environments) and Petri-nets. A prototype of a smart car space is also described.

An architecture for connected vehicles and fog computing that provide for rich connectivity and interactions among vehicles (V2V) and infrastructures (V2I) is presented in [11]. The envisaged services are infotainment, traffic and public safety, real time traffic analysis, support for high mobility, location awareness and so on. The architecture includes virtual sensing zones, access points (RSUs), M2M gateways, and the fog computing cloud. No implementation of this architecture is available. A cooperative fog computing architecture (bird's eye view) is proposed also in [12]. Possible services for IoV applications are discussed, including mobility control, multi-source data acquisition, distributed computation and storage, and multi-path data transmission. The architecture is analyzed based on simulations on efficient resource management. In [13], a high-level architecture of vehicular fog computing is shown, which includes smart vehicles as data generation layer (data gathering/pre-processing and vehicle level decision), the RSUs'/fog nodes' layer (data fusion/pre-processing and area level decision), and the cloud servers' layer (data exploitation and analysis, city level decision). A potential fog assisted traffic control system is used to explain the architecture.

IV. ARCHITECTURE FOR SMART CONNECTED VEHICLES AND VEHICULAR CLOUDS

A. The Expected Services

Similar to other important instantiations of IoT, the IoV is expected to offer communications, storage, intelligence, and learning, via the vehicular clouds and fogs that provide for all the services required by the autonomous vehicles (which are able to anticipate their users' intentions) [5, 6, 11-13]. In our view, the main services expected from smart connected vehicles "operating" within IoV are as follows:

- *Driver and passengers safety*: smart new pervasive computing specific services, in addition to the vehicle's built-in safety mechanisms;
- *Vehicle security, privacy, trust*: alerts and warnings, alarm systems, intrusion detection etc.;
- *Vehicle maintenance and safety in real time*: status, diagnostic, periodic technical inspection, periodic service and maintenance etc.;
- *Vehicle management*: fuel efficiency, efficiency, cost control and savings, alerts for upcoming payments financing/insurance, fleet management, monitoring;
- *Vehicle monitoring, tracking, analysis, reporting, alerting*: low battery power (showing the closest recharging facility), low fuel (showing the closest gas or power stations), automatic error codes interpretation, analysis of vehicle performance;
- *Sustainability*: reducing pollution (noise, gases, after discarding), reducing costs, increasing reliability, safety, and lifetime;
- *Commercial and public services while-in-car*: automatic toll collection, infotainment, advertisement, travelling planning and assistance;
- *Commercial services car-related*: car sales, financing and insurance, car sharing (availability noticed in real-time for possible passengers), new ownership types;
- *Traffic management and active on-road safety (both humans and vehicles)*: cooperative navigation, GPS-based navigation, speed management and adaptive cruise control, warnings (lane changing, wrong way, signal violation, traffic condition or event, pre-crash etc.), smart parking, exchanging road traffic information with nearby vehicles, automatic emergency call in case of critical situations (accident, hijack etc.), broadcast vehicle location to other vehicles not in visual range;
- *Driver assistance, reflective driving*: driving behavior analysis from vehicle data, driving patterns;
- *General purpose computing* provided that the on-board computers will become more general and "prone" to computationally intensive tasks.

Further, the smart environments, in which vehicular clouds and fogs exist and work, are expected to provide for autonomy, reactivity, pro-activity, openness, hierarchical organization, rational behavior, learning, mobility, reasoning, agility, flexibility, decentralized control, adaptability, modularity, self-organization, dynamic reconfiguration, scalability, robustness, and even social ability through human interface. In such spaces, a huge variety of scenarios is possible. For example, using the smart in-vehicle sensors, the connected vehicle can detect that the driver is not driving safely and can provide him with some audio advice about how to improve his driving style. Or, at rush hours, the driver can be provided with alternative faster routes. In case of a crash in a remote area resulting in no humans able to call the emergency services, the autonomous connected vehicle or the smart environments or both can make that call.

B. The Proposed Adaptable Architecture

In this sub-section, we introduce a high-level adaptable architecture (called Savvy) that can be used for modeling both smart connected vehicles and their smart surrounding environments (Fig. 4). The abstraction layers are described further on, highlighting for each one what is modeled for smart connected vehicles (V) and, respectively, for smart surrounding environments (E). However, despite these particularizations, this architecture is general and can be adapted for any smart spaces and environments.

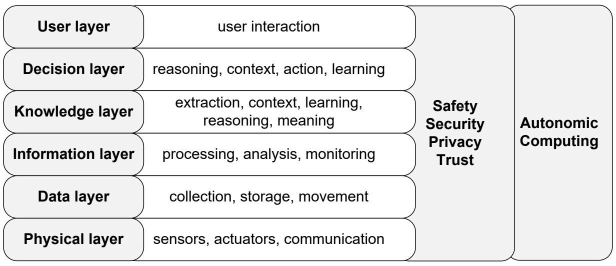


Fig. 4. Architecture for smart connected vehicles / environments

Physical layer **V**: sensors, actuators, communication devices, vehicle interfaces, other (intelligent) devices (alarms, tracking); **E:** road sensors, actuators, communication networks, surveillance systems, other physical infrastructures in houses, buildings, parking lots, shopping centers and so on.

Data layer **V:** unorganized data collection, storage - local on vehicle or remote in the surrounding smart environment, data communication channels; **E:** unorganized data collection, storage (remote in the surrounding smart environment), data communication channels or other data sources available.

Information layer **V, E:** data processing, analysis, monitoring, visualization etc., which is contextualized, categorized, calculated, condensed; the difference between the vehicle information layer and the environment information layer is that only some parts of the vehicle information will get to the cloud/fog or environment, when necessary; various information sources available.

Knowledge layer **V, E:** knowledge extracted or discovered from data and information, understanding, experience, insight, intuition, contextualized information, facts, stories, synthesis, wisdom; while this layer is similar in its essence for both smart spaces, they are expected to "make sense" and get meaning from information that is specific to each space - for example, the connected vehicle may "learn" to recognize what state the regular driver is in, i. e. she is tired, distracted, unfocused etc.; the smart environment may extract traffic patterns for various times or for special situations such as a sportive manifestation that will gather tens of thousands of people and cars in a specific location; various information and knowledge sources available.

Decision layer **V, E:** rules, case-based-reasoning, intelligent knowledge-based decisions, learning, planning and control; **V:** based on the knowledge extracted or discovered on the previous layer, the connected vehicle can make recommendations or can take action (provided that the vehicle is autonomous), appropriately, in various situations. **E:** traffic management decisions to improve traffic fluency at rush hours or, in case of events attended by many people and vehicles.

User and application layer **V, E:** users can interact directly with both spaces, via specific interfaces or applications, to use a large variety of services; Users can be drivers, vehicle owners, passengers, pedestrians, fleet managers etc. and they are at the very core of this architecture, built around them and their needs.

Safety, security, privacy, and trust: although privacy and security are actively researched in VANET (Vehicular Ad hoc Network), Vehicular Clouds, and Smart Environments, there is no consensus yet on standards or solutions, mainly because of both concept novelty and specificity. In VCs, a lot of issues are challenging, i.e. large number of nodes, their high mobility, heterogeneity and spatial distribution, intermittent and short-lived wireless inter-vehicle communication, frequent change of cloud topology, network scalability, "equality in crime between the users" (in the sense that the attacker can be physically located in a vehicle in the cloud), autonomous cooperation between vehicular resources and some others. **V, E**: in our view, all these can be provided by a unified framework that integrates synergically well-known solutions from traditional networks, distributed computing, and VANET with those devised specifically for vehicular clouds and smart environments, including, new approaches [3, 5, 13-15].

Autonomic computing refers to a computing environment capable to manage itself and to dynamically adapt to change accordingly with business policies and objectives. Self-managing environments can carry out this kind of activities based on situations they observe or sense in the IT&C environment rather than requiring humans to initiate them. Consequently, these environments are self-configuring, self-healing, self-optimizing, and self-protecting [16]. *Autonomy implies self-governance and self-direction, whereas autonomic implies self-management. That is autonomy/self-governance is the automation of responsibility including some decision making for the success of tasks/objectives whereas autonomicity/self-management is the automation of responsibility including some decision making for the successful operation of the system* [17].

C. *Implementation in a Smart Connected Vehicle*

The proposed architecture has been partially implemented within a *near-real-time* vehicle tracking system (Gipix), which we have been developing over the last 15 years. The system is in use on more than 500 cars. Gipix collects the data of interest by using a GPS-based embedded device developed in-house. Its main capabilities include *one-second acquisition interval (position, speed, and heading), high antenna sensibility, interoperability, adaptability, local data storage, and positioning without GPS signal based on the position of the GSM cells.* It has a number of sensors that allow gathering of abundant information about both the vehicle and the driver. The tracking device provides for transmission of all the information about position, sensor values, events, etc. to the central tracking server or directly to the driver's mobile phone. Usually, the communication is done using the GSM network, and due to the low requirements of data traffic, the low-speed GPRS connectivity is used (9600 bps). Data transmission is performed with relatively low total costs by using our optimized data management scheme. The system can also provide statistical information about different aspects of the recorded data, e.g. the driver's acceleration/braking habits, the speed variations, or a detailed analysis of the driving style. Even GPRS is in the end of life phase, it still has the greatest geographical coverage in Europe as opposed to 3G, 4G, 5G, mainly in large population areas (where we aim to build smart cities and infrastructures). However, our system can still be used on these networks without any change, by just using a different hardware communication module (because we are on a higher level communication protocol in the Internet).

SAVVY's implementation in *a smart connected vehicle* able to work within a smart environment and to provide for autonomic, pervasive, and fog computing is shown in Fig. 5. Multiple sensors (S) and actuators (A) work together, collecting and measuring data, respectively controlling devices. Several *task subsystems* provide for collecting information about the vehicle itself, communicating, managing the alarm system, guaranteeing safety and security, autonomic computing etc. *Service Interface & Control (SIC)* is activated either to respond to service requests or to pro-actively perform some support actions or activities for various requests (users' included), such as data acquisition/storage, alarms, communication, etc.

The Intelligent Decision module ensures "the smartness" of the in-vehicle space through the knowledge and decision layers described in the previous section (e.g. the driver's style analysis [18]). However, a part of the intelligent decision resides with humans because, in our opinion, no matter how smart machines are or could become, they should not have the final decision (this is why we use mostly the word *autonomic* and not *autonomous* with regard to smart vehicles).

Moreover, *based on the same architecture*, other customized systems can be built. They can be used in other pervasive and fog computing applications such as energy consumption monitoring, ubiquitous health monitoring, traffic and public safety, real time traffic analysis, airport (or mall) data centers, parking lot data clouds, etc.

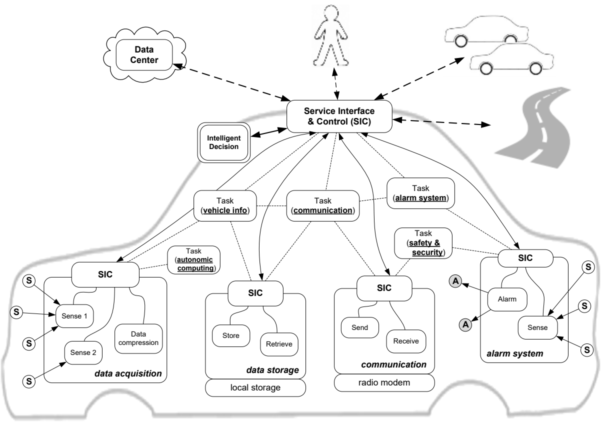


Fig. 5: The smart autonomic connected vehicle.

V. CONCLUSIIONS AND FUTURE WORK

Smart, pervasive computing environments can be seen as ecosystems of ever growing complexity that have not yet proved their true potential to make life simpler by being able to sense, adapt, and respond to human needs, and in which devices can act as portals into various application-data spaces, not just as repositories of custom software to be managed by users. Therefore, it is vital to provide a standard model for common IoT-based services that guarantees interoperability, portability, and manageability. However, creating and implementing it is very complicated because it is based on sensors, networks, intelligent analysis, and intelligent actions and there are challenges related to all these components. IoT implementations *to the edge* (fog/edge computing [5, 6, 11-13]) can provide a viable solution mainly because, in this case, the bulk of the application logic, data storage, and analytics is placed on the actual device instead of a cloud. Vehicular fog computing extends the fog computing paradigm to conventional vehicular networks.

The work presented in this paper addresses some of the challenges summarized above. We introduced here a user-centric adaptable architecture for both smart autonomic connected vehicles and their smart surrounding environments. Our view is user-centric because the human user is able to benefit from the services offered without being overwhelmed or overpowered by them, either by making explicit requests and/or by getting support any time the smart environment "realizes" that she needs help. Despite this instantiation, the architecture is general and can be adapted for any smart spaces and environments. As future work, we consider developing further the smart connected vehicle by including more autonomicity features and by providing more of the services offered by the proposed architecture. Also, we aim to extend connection and interactivity between the vehicle and the environment in which it operates.

Along the way, the conceptual work needs to be refined and kept in pace with the evolution in the field. The following wave of innovation is expected to improve many aspects related to technology, standards, *humanization of Things*, business, society, etc. Hopefully, our work here will be a step forward to implementing *IoT as a Service* and to providing for more pervasiveness, but we are aware that there is still a long way to go towards that desideratum and, further, towards the higher goal of IoV significantly improving our daily life.

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