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An end-to-end 5G Automotive Ecosystem for Autonomous Driving Vehicles

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ABSTRACT

The fifth-generation (5G) of mobile systems is considered a key enabler technology for autonomous driving vehicles. This is due to its ultra-low latency, high-capacity, and network reliability. In this paper, a full end-to-end 5G automotive platform for benchmarking, certificating, and validating distinct use cases in cooperative intelligent transport systems, is proposed. Such an automotive platform enables fast service creation with open-access and on demand services designed for public use as well as for innovative use cases validation such as highway chauffeur system, truck platooning, and real-time perceptive intersection, to name a few. The distinct set of technologies that compose the end-to-end 5G automotive ecosystem framework is described. The holistic 5G automotive ecosystem can handle system and networking interoperability, handover between mobile cells, mobile edge computing capabilities including network slicing, service orchestration, and security. Moreover, the latency performance of a vehicular network with two vehicles is experimentally addressed by using the holistic platform. Up- and down-stream packet transmissions between the two vehicles in an open environment with real-traffic conditions is considered. The results pave the way towards latency levels within the range of 5G key performance indicators and consequently enabling autonomous driving systems. The 5G platform can be further useful for governmental agencies to define new policies and regulations, being able to address critical points such as data protection, liability, and legal obligation, regardless whether systems are partially or fully automated.

Keywords: 5G, LTE-V, THz, light-fidelity (Li-Fi), visible light communication (VLC), autonomous driving vehicles, mobile edge computing (MEC), artificial intelligence (AI), software-defined networking (SDN)

1. INTRODUCTION

The significant advances in information and communication technology are changing the industrial sector of automotive and mobility, allowing new services and solutions to be develop into cooperative intelligent transport systems (C-ITS) [1]-[3]. New technologies to ensure safer roads have become of paramount importance to cope with growing traffic congestion, heavier traffic loads, and dense transport logistics involving terrestrial goods transportation. In 2015, around 1.25 million people died globally in traffic accidents. This generated an associated governmental cost circa 3% of the gross domestic product in respected countries (according to figures from the World Health Organization). The fifth generation (5G) mobile systems [4]-[8] are a prospective technology candidate to allow autonomous vehicles to become fully connected at all times. This enables autonomous driving vehicles to safely navigate all types of roads which, in turn, helps to reduce traffic accidents and fatalities. 5G systems can deliver higher capacity, significantly faster transmission rates, and better coverage range with greater number of installed towers and cells. However, the 5G development is still underway with room for several different complementary technologies to be exploited. A new era of autonomous driving vehicles will most likely be composed of several different technologies with different functionalities and purposes. Note that 5G cellular vehicle communication systems are currently under development and have a long way ahead until it becomes mature and consolidated within the automotive industry.

A single based technological solution like, for example 5G or IEEE 802.11p might not be capable of providing and supporting the full range of C-ITS services as well as networking capabilities needed of the vehicle of the future. In addition, the complete driving task is too complex to be fully formalized via a single technology as a sensing-acting robotic system for achieving full autonomous driving capabilities. This holds particularly true for real-world driving operation where the margin of allowable error is extremely small, and the number of edge-cases is substantially large [9]. Accordingly, a hybrid solution, combining complementary communication technologies is of paramount importance. Likewise, a heterogeneous vehicular networking system that leverages the best of distinct integrated technologies is perceived here to increase road safety while also anticipating the needs of emerging and yet, unforeseen business cases. The combination and leverage of 5G, light-fidelity (LiFi), and terahertz (THz) communication systems combined with mobile edge computing (MEC) systems (including artificial intelligence (AI), software-defined networking (SDN), slicing, security, and network function virtualization (NFV) functionalities), will create many innovative business cases within the automotive and mobility industry. They will also help to address safety issues in general autonomous and cooperative applications. Indeed, the integration of 5G, LiFi, and THz systems are a prospective solution for vehicular networks.

Visible light communication (VLC) systems [10]-[12], including Li-Fi [13], [14], are regarded as a complementary solution for 5G systems. This is due to the unique advantages offered by VLC/Li-Fi such as free-frequency license, no electromagnetic interference, and ease of deployment with low costs as compared to fiber deployments. Moreover, VLC has greater bandwidth available than radio frequency (RF) systems and can achieve high data rates (tens of gigabits). Consequently, it can cope with KPIs providing low latency and extended service life. Li-Fi is further being employed in C-ITS and autonomous driving vehicles for improving the efficiency of transport systems, and eventually, reducing CO₂ emissions. Furthermore, Li-Fi systems are regarded as an elegant solution for wireless communication between vehicles or between traffic infrastructure and vehicles. This means vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication systems [15]-[21] can be combined with RF systems enhancing the overall capacity. Nonetheless, THz wireless systems have emerged as a new technological trend to support unprecedented large data volumes (in the order of peta bytes) that will be generated by autonomous driving vehicles. THz systems operate within 0.1 and 1 THz spectrum region and have a large bandwidth capacity available [22], [23]. This huge availability makes them strong candidates for both intra- and inter vehicle communication.

Regardless of the specific technology or combination of different technologies, automated vehicle platooning is expected to have a significant impact on overall fuel consumption. When heavy good vehicles can drive close together more efficient road usage is achieved with less congestion, faster throughput and reduced CO₂ emissions. Vehicle platooning means vehicles follow in a convoy with between 1 and 3 meters separating the vehicles. This, of course, means a much-reduced braking distance. In case of emergency braking by the lead vehicle, the network must be responsive enough to ensure that the rest of the vehicles behind brake immediately, essential if collisions are to be avoided. For improving safety with an inter-vehicle gap in the range of one meter in vehicle platooning systems, the braking distance should be around 0.028 meter. In current 4G networks, the latency is around 50 ms, which would allow a vehicle to move 1.4 meters from the moment that the sensors on the lead vehicle detects an obstacle on a collision course and executes the braking command to all the vehicles behind. By contrast, the combination of several technologies including 5G and MEC functionalities can provide latency levels as low as 1 ms, which would allow the vehicle to move 0.028 meters only, and thus avoid the possible collision. Indeed, latency is considered a key enabler KPI for successful implementation of autonomous driving vehicles.

Within this context, in this paper, we introduce and describe an end-to-end 5G automotive ecosystem composed of many distinct technologies for benchmarking, validating, and certifying different use/business cases based on C-ITS (such as highway chauffeur, advanced driving intersection assistance, and truck platooning). The end-to-end 5G automotive ecosystem can handle system and networking interoperability, handover between mobile cells, MEC capabilities including slicing, service orchestration, and security. This automotive ecosystem enables fast service creation with open-access on demand for general public (SMEs, start-ups, etc), in a bureaucracy free environment for use/business cases validation. The different technologies such as 5G, LiFi, THz, and MEC are described. We describe the vehicular network architecture and experimentally evaluate the performance of the latency considering LTE sidelink mode 4 technology and packet transmissions between two vehicles. The experimental results show that good latency levels are obtained with most packets received under 40 ms, representing substantial progress in enabling autonomous driving systems, even when the network functionalities are not fully used. These preliminary results have proven to be valuable insights and pave the way towards the next stage of development of the ecosystem platform with the goal to achieve ultra-low latency levels (1 - 5 ms) as promised by 5G KPIs. Finally, the 5G automotive ecosystem is further

useful for helping public authorities in defining new policies and regulations concerning automated driving systems. This is essential to adapt the current legal framework by considering key points such as data protection, liability, and legal obligation of individuals and stakeholders, regardless of whether systems are partially or fully automated.

2. TECHNOLOGIES FOR AUTONOMOUS DRIVING VEHICLES

This section addresses the different technologies enablers of innovative autonomous driving solutions, cooperative systems, and unforeseen use/business cases with ultra-low latency, 99.99 % network reliability, and super-high capacity. Accordingly, the leverage of 5G [24]-[28], MEC [29]-[32], LiFi, and THz [33]-[36] technologies grants not only an agile end-to-end automotive ecosystem platform for fast service creation, benchmarking, and field trials, but also allow developments and solution extension based on compute-intensive applications within industrial domains such as Industry 4.0, harbour cranes automation, and health care systems.

2.1 Visible Light Communication Systems

VLC systems can be implemented via light emitting diodes (LEDs) from already deployed lighting infrastructure in vehicles, traffic lights, and Industry 4.0. VLC systems are considered energy efficient as they do not use extra energy for data transmission, except the energy already used for lighting the environment. It is worth mentioning LEDs are widely used in vehicle lighting systems and traffic lights. Moreover, VLC/Li-Fi technology[15]-[21] is compatible with traditional RF systems in the way that they can be complementary to each other and consequently enabling new use cases, functionalities, and relieving network requirements.

The VLC technology employs visible light as a carrier for data transmission and is considered a promising alternative to the existing RF-based wireless systems. Normally, a VLC network can be realized via a LED transmitter to convert data signal into an intensity modulated optical signal. In the simplest approach, on-off keying (OOK) modulation is employed as it is considered simple to implement, but advanced modulation formats can also be used. The obtained modulated optical signal is transmitted through the VLC channel with line-of-sight (LoS). At the receiver side, the optical signal is filtered by optical filter to remove the unwanted spectrum components and then by using lens is focused on a photodetector obtaining the electrical data signal that further is demodulated and decoded by the decoder. VLC systems are regarded as a promising candidate for V2V and V2I communications in autonomous vehicles networks [20].

2.2 5G Mobile Systems

5G systems accounts for a new networking architecture scheme with small-cell coverage based on cloud radio access network (C-RAN), where legacy base station (BS) functionalities are now split into two main parts: centralized baseband unit (BBU) and remote unit (RU) [24]-[26]. Generally, a 5G C-RAN architecture regards the relocation of BBUs from the RU premises to the central office (CO) site creating a centralization of BBUs. This scheme grants the system several advantages like higher flexibility and manageability, reduced power consumption, to name but a few. The RU is connected to BBUs using analog or digital radio-over-fiber (A-RoF or D-RoF) protocols [25].

Fig. 1. Network scenarios using the combination of different technologies based on 5G, light fidelity (Li-Fi), and terahertz (THz) systems for autonomous driving vehicles.

Normally, a 5G RoF system based on mm-Wave transmits a digital baseband signal through a fiber link, undergoes optical to electrical conversion (O/E), and upconversion to a mm-Wave frequency, and then is radiated, detected, and downconverted to baseband frequency. Note that legacy mobile systems have their RU and BBUs physically located at the same cell tower with a coaxial wire connection from the top of the tower to the bottom of the tower. A 5G C-RAN fronthaul can operate in the mm-Wave range with multiple bands within the frequency range of 20 to 300 GHz. The approximate coverage areas are up to a few kilometres within K/Ka-band and up to a few hundreds of meters within the V-band region [24]. Although the mmWave bands extend all the way up 300 GHz, it is the bandwidth range from 25 GHz up to 100 GHz that are expected to be used for 5G mobile systems. Interestingly, the short wavelength of mmWave signals can fit a larger number of antenna elements within the same or even a smaller footprint as current sub-6 GHz antennas. Consequently, this allows the use of several antenna arrays with thousands of antenna elements, which was impractical in the previous generation of mobile systems due to form factor and size restrictions of such elements.

2.3 Mobile Edge Computing Nodes

The MEC node concerns a group of functionalities and technologies achieved via AI, SDN, NFV, slicing, service orchestrator, and traffic classification. SDN can resolve the vertical integration of current network environments by decoupling the control plane (i.e., control logic) from the data plane (i.e., data forwarding equipment). With such an architecture, routers and switches become simple forwarding network elements whose control logic is provided by an external entity called SDN controller or network operating system (NOS). Northbound interfaces (NBIs) offered by a logically centralized SDN controller allow different network applications (firewalls, routing, and resource orchestrators) to implement network control and operation logic. In addition, other type of high-level NBIs category are implemented as NOS management applications. Examples of this category include virtual tenant networks, application-layer traffic optimization, and intent-based networking (IBN). In SDN, the concept of orchestration is vital to automate network operations properly. SDN network domains need single-domain or multi-domain orchestration systems to coordinate end-to-end connectivity services through different network domains controlled by different SDN controller instances, which in turn must communicate directly with the physical network.

Furthermore, the leverage of IA and SDN capabilities can rise a system framework in which software and hardware from different vendors can be used with ease and flexibility, instead of being limited to a specific commercial and proprietary solution. To put it simply, the IA system of the SDN-orientated solution considered here is transparent for the network hardware components and can be run remotely in the MEC node. The SDN networking paradigm along with IA is leveraged to have control over the data flow. On the top of that, both SDN controller connections to the 5G towers can be achieved by leveraging the 5G systems that by its turn enables network topology change on demand, consequently adapting to the changing needs of different conditions, traffic, and urban environments. By its turn, network service orchestration has become a key feature to enable the delivery of different 5G KPIs. A framework orchestrator focuses on the support VNF operation across different hypervisors and computing resources. It also covers the orchestration and lifecycle management of physical and virtual resources. In the NFV context, NFV-MANO defines the orchestrator with two main functions including resources orchestration across multiple VIMs and network service orchestration.

Network slicing will take into account physical/spectrum, computational and storage resources, sensor gateways, small cells, and fog servers, to enable the appropriate placement of VNF, security, service orchestration, and traffic prioritization. The MonteBox functionalities includes virtualized RAN (vRAN) to fully virtualize the 5G infrastructure elements. This approach will seamlessly interface the interacting facility user with the entire underlying 5G RAN environment, ensuring that a) a diversity of wireless communication technologies can be served and b) edge network logic can be utilized for dynamic and de-centralized service deployment. Its capability of accommodating in dynamic manner, user service logic on the edge network comes to fulfil the requirement for network resilience and transparency, so that network agnostic service can be provided either locally on specific network branches or at a global level.

2.4 Terahertz Communication

Communication systems in the THz frequency range has received increased attention recently fostering several new possibilities and applications [33]-[36]. THz systems are enablers of inter- and intra-vehicle communication in a way that vehicles can communicate with one another, traffic lights, and provide intra-connectivity to devices and components in the inner part of the vehicle. The latter, enabled by THz wireless systems, can build a wireless personal area network inside a vehicle supporting high-speed transmission rates. THz wireless systems can be considered a complimentary solution to work along with 5G and LiFi networks. These technologies are complementary in many respects and should be integrated according to network requirements.

With autonomous driving vehicles becoming a sort of mobile data center due to the large amount of traffic they are expected to handle in the soon future, in order of peta bytes, THz systems have become a key technology to satisfy real-time traffic demand in heterogeneous networks by easing the spectrum scarcity and capacity limitations of current wireless systems [35], [36]. Accordingly, THz wireless systems can offer a large enough bandwidth and satisfy this new data increasing trend in autonomous vehicles. To do so, new techniques for signal generation, wireless transmission, and data recovery have been investigated [36]. The frequency range between 300 GHz and 3 THz offers huge bandwidths of several tens of GHz, and as an example, the first standard for THz communication (IEEE 802.15.3d) considers transmission rate up to 100 Gb/s. Although obstacles like trees, poles, and concrete fences can block THz signals, autonomous relaying technologies can be used to remedy these issues. For example, vehicle relays can be used to create an ad hoc network among several autonomous vehicles so that they can bypass obstacles and keep the communication system functional. Nonetheless, THz systems can surprisingly support up to 100 m links with directional antennas and up to 10 m with omnidirectional antenna [33]. The frequency range of the different wireless technologies can be found in [36].

3. AUTOMOTIVE NETWORK ECOSYSTEM ARCHITECTURE

In this section, we describe the vehicular network architecture and infrastructure including integration of different telecommunication technologies, which is referred here as end-to-end 5G automotive ecosystem network infrastructure. The automotive ecosystem platform supports a flexible network system concerning an integrated core and metro network providing optical light-paths to the RAN [24]-[26]. The holistic ecosystem will be controlled and orchestrated via automation schemes and programmability features based on open controllers, protocols and interfaces, which will enable features such as hardware disaggregation of the optical nodes and radio network nodes as well as computation and the features required for verticals such as automotive. In addition, network virtualization enables the coordination via a purposely designed control plane that leverages upon years of well-established SDN and NFV research to enable network slicing, capable of reliably supporting verticals in terms of quality of service and quality of excellence for different application.

The end-to-end ecosystem platform for automotive testing purposes with ongoing 5G mobile systems deployment are in the Brabant region, in The Netherlands. The field tests provide a realistic, but controlled, open-sky setting for experimental performance evaluation and comparative testing of distinct technologies such as LTE-V, IEEE 802.11p, LiFi and 5G. The platform is equipped with V2I (vehicle-to-infrastructure) roadside units, dome cameras, intelligent traffic light controllers (iTLCs), a nearby facility for data processing and a MEC node. To experience high performance, different cells are linked to a MEC located near the road infrastructure along with a mobile gateway connected to a RAN. The MEC node deployed surrounding the road infrastructure runs V2X applications. The MEC system is based on innovative technologies such as AI, SDN, NFV, network slicing and virtualization, and traffic classification schemes, as depicted in Fig. 2. The platform also has a dedicated evolved packet core located close by the road infrastructure.

Fig. 2. End-to-end 5G automotive ecosystem: local optical ring along with the mobile edge computing and its functionalities (software defined networking, network function virtualization) for enabling autonomous driving vehicles and cooperative intelligent transport systems.

Fig. 3. Evolved Node-B (ENodeB) station with access to the local mobile edge computing (MEC) node and transmitting data to vehicles. The vehicles can transmit both cooperative awareness message (CAM) and decentralized environmental notification message (DENM).

Furthermore, testing vehicles are equipped with LTE-V, C-V2X, enhanced GPS technology, LiFi, and IEEE 802.11p. In this way, direct and indirect cellular communication among vehicles are possible. The vehicles can transmit both cooperative awareness message (CAM) and decentralized environmental notification message (DENM). Usually, vehicles follow a longitudinal trajectory, and rely on the MEC node for intensive networking tasks. This is illustrated in Fig. 3. While the communication scenario of V2V is defined by messages originating from vehicle-to-vehicle, V2I can be more complex due to many possible different topologies of the ITS network infrastructure. Note that the use of long-range cellular communication for V2V services renders a V2N2V communication scheme, where “N” represents the backend comprising servers, communication lines, and related ICT services. In a typical message-queueing implementation, multiple queues are defined in a message queue (MQ) server. An application registers with the MQ server and listens for messages placed into the queue. Other applications connect to the queue on the server and transfer messages onto it. The MQ server stores the messages until a receiving application is available and then sends the messages to the receiving application, which then processes the message in an appropriate manner. A common aspect of MQ servers is that they separate the actual message being transmitted from the protocol and logic of handling the messages. The MQTT is the MQ protocol used as the message protocol for interfaces.

Regardless of the protocols used in the server, several standards are currently under developed. The LTE-V2X2 was standardised by the 3GPP in 2016 under the umbrella of LTE Release 14 and encompasses two interfaces: (a) a wide area network LTE interface (Uu) that connects end-user devices and vehicles to mobile network base stations and core networks, for provision of Internet and vehicle to network (V2N) services; and (b) a direct communications interface (PC5) that connects vehicles to vehicles (V2V), to roadside infrastructure (V2I) and to pedestrians and other vulnerable road users (V2P), for provision of low-latency and high-reliability vehicular services. The LTE-V2X interface does not necessarily require assistance from a mobile network. Finally, the user equipment is placed in the vehicles and connected via UTP to an onboard computer. The timing in the vehicles is configured to at least 10 Hz, but each sort of message has its own frequency. The timing in the vehicles are synchronised by using a GPS.

4. LATENCY PERFORMANCE EVALUATION

In this section, the experimental latency investigation considering two vehicles is addressed as part of initial field trials of autonomous driving systems. An accurate definition of latency is given by 3GPP TS 22.261, where latency is defined as “the time that takes to transfer a given piece of information from a source to a destination, measured at the communication interface, from the moment it is transmitted by the source to the moment it is successfully received at the destination”. Thus, in contrast to the concept of round-trip time, this definition accounts for the one-way transit time between source and destination. It is worth mentioning that there are several definitions of latency and it may change from source to source.

To reduce the fuel consumption in a vehicle platooning and CO₂ emissions, the vehicles should be close to one another but still at a guaranteed distance enough to break immediately in case of an emergency. A large volume of data transmission is needed for such a close coordination of vehicles within a very short physical distance and time duration. Data exchange ensures all vehicles are constantly updated about their status. Only a combination of several technologies can be able to guarantee such a challenging braking distance as well as ultra-low levels of latency. Several latency specifications can be found in the draft of the 3GPP standard TS 22.186 based on the use case and level of autonomous driving. The desired latency value depends on the use case as well as level of automation. For example, in cooperative adaptive cruise control levels below 40 ms are accepted.

Then, to carry out some field trials based on the vehicular network platform and to address the experimental performance evaluation of the latency, two vehicles (manually driven) were considered and instrumented for safety precaution purposes driving on busy road conditions with real vehicle traffic. The master (vehicle #1) was driving in front of the slave (vehicle #2). For the scenario of this evaluation, only messages related to mobile data transmission and autonomous driving were considered; more specifically, CAM and DENM messages. During the field trial, the two vehicles transmitted approximately 55000 messages with approximately 100 bytes each, in a bi-directional link. Furthermore, the messages are transmitted by using power levels of 11 dBm and quadrature phase-shift keying modulation. Finally, it is worth pointing out that we consider LTE sidelink mode 4 with direct V2V communication over PC5 interface for the performance evaluation of the latency.

The one travel trip latency versus the transmission time of packets is plotted in Fig. 4 for both vehicles. Vehicle #1 transmits packets to vehicle #2 (blue) and vehicle #2 transmits packets to vehicle #1 (red). Note that clock the synchronization between both vehicles is considered accurate. Results show that the overall latency experienced by the two vehicles' communication channel is similar, i.e., symmetric channels. The maximum obtained latency value is around 100 ms (see red peaks in Fig. 4); nonetheless, for realistic and accurate latency levels, the 99th percentile of the entire collected data should be considered, and for this case the latency is below 50 ms. The average of the latency considering the entire data set is approximately 22 ms. Furthermore, the experimental results show that approximately 97 % of the messages are transmitted and received within 40 ms latency. Therefore, the results are in good agreement with technical expectations and represent a step further towards genuine autonomous driving vehicles. Full details including further results and analysis on the vehicular network operating under the holistic mobile ecosystem will be published elsewhere. Finally, the real-world driving data collected might be useful for the development of new deep-learning models to cope with channel prediction, intelligent computation task offloading, and efficient use of vehicles' controllers [37]-[40].

Fig. 4. Latency versus transmission time of packets for the autonomous driving vehicle systems.

5. CONCLUSIONS

In this paper, we proposed and described a full end-to-end 5G automotive ecosystem platform for benchmarking, validation, and certification of different use/business cases within the scope of cooperative and autonomous driving systems. The 5G ecosystem platform can be further useful for governmental agencies to define and evaluate new policies and regulations partial and fully concerning automated driving systems considering critical points such as data protection, liability, and legal obligation, regardless of whether systems are partially or fully automated. Moreover, we described the innovative integrated technologies that form the platform, i.e., 5G, LiFi, and THz systems as well as MEC node with several functionalities.

We also assessed a key 5G KPI responsible for enable autonomous driving vehicles, namely, latency. Accordingly, we experimentally addressed the latency performance evaluation of a real-world vehicular network based on LTE sidelink mode 4 technology with communication over PC5 interface. We built and implemented, along with several local partners, the communication system and evaluated it considering a vehicle-to-vehicle channel in a field trial. A set of different technologies including both software and hardware were implemented as part of the holistic communication system. For example, MEC functionalities, message broker, LIDAR, cameras, GPS, and LTE-V technology. We considered up- and down-stream packet transmissions between two vehicles (manually driven) in a scenario with real vehicular traffic conditions but under fully safe and controlled conditions. Preliminary results shown that 99th percentile latency stays below 50 ms and that 97 % of the transmitted packets arrived within 40 ms. Thus, the initial results provide valuable insights towards next stage development of a robust and safe automotive ecosystem for offering users ultra-low latency (< 5 ms) and full capabilities. Further tests, field trial experiments and data analysis will be carried out during the next research stage and published elsewhere. Finally, we will investigate as future works vehicular networks and obtain further real-world traces with more involved vehicles like truck platooning, over multiple locations.

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