Intelligent & Ultra-Reliable Connectivity for Safety Services in Road Tunnels: A System Architecture

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Safety within road tunnels is critical for traffic safety. With the rapid growth in sensor and communication technologies, the concept of "smart tunnel" has been envisioned where by leveraging sensory data, smooth and safe flow of traffic is ensured. A prominent signature of such tunnel is coordination among the road elements in the context of C-ITS, facilitated by communication technologies. Road tunnels represent challenging environments for communication due to their unique properties. However, there is a growing demand for ultra-reliable communication within the tunnels, particularly to introduce novel C-ITS safety services. The traditional methods that are aimed at supporting public radio broadcasting and push-to-talk services do not satisfy such demands. In this paper, we study the state-of-the-art of communication technologies for safety services within the road tunnels and identify their challenges, operational requirements and suitability for safety use-cases. Further we focus on disruptive technologies such as 5G cellular networks and the new opportunities that arise from their deployment within the tunnels. Finally we propose a generic 5G-based communication architecture that leverages the use of VEC and URLLC to meet the ever-increasing demands. We highlight that such architecture allows for radically shortening the design and deployment cycle of novel safety services within the tunnels from several years to weeks.

Keywords: Tunnel safety, telecommunication, reliability, system architecture, VEC, C-ITS.

1. Introduction

Safety and emergency management within road tunnels are critical elements of assuring safe and efficient flow of traffic within the road network. Being an integral part of public road system, tunnels can be viewed as complex sociotechnical systems since they play an important role in the general notion of public safety Njå and Svela (2018). Common threats to tunnel safety are fire, collisions and toxic fumes/gases Sun et al. (2019); Qu et al. (2013). To mitigate the risks and improve safety, various measures are commonly undertaken aiming at prevention, detection and response to incidents. For instance, preventive measures include installment of emergency telephone lines and evacuation rooms, whereas detection measures include the use of video surveillance or sensors for AIDS. Further, response measures include the use of firefighting and ventilation equipment and the operation of emergency responders. Almost in all cases, *communication* is a key element to the safety operation within the road tunnels – e.g., telephone lines require a communication backhaul that assures connectivity to the CTC or emergency response entities, that is resilient to the failure in presence of infrastructure damage Ho and Hsu (2014). On the other hand, video surveillance and AIDS require a similar communication backhaul albeit with higher network traffic capacity and lower latency, in order to provide a real-time overview of the entire tunnel system to the CTC or other road system elements.

Traditionally, such backhaul has relied on Ethernet-based links – e.g., using ring protection mechanism specified in ITU G.8032 recommendation (ITU) (2020) for fault-tolerance and high reliability in harsh environment of road tunnels. It provides a mean for connectivity between various RSUs as well as to/from the CTC. This serves stationary safety solutions on the last hop – e.g. emergency phone booths and surveillance cameras. On the other hand, in dynamic emergency scenarios where emergency responders or the objects of interest are likely to be mobile, it is often necessary to be able to communicate with the road elements using some form of wireless technology on the last hop. A typical use of wireless in tunnels is leveraging DAB+ ETSI (2020a) to provide audio-based safety instructions to road users. On the other hand, other wireless technologies such as Tetra ETSI (2020b) or Project 25 (P25) (APCO)

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(2020) that are widely used for push-to-talk audio dispatch services among emergency responders are being increasingly deployed in tunnels.

However, aforementioned technologies have a very limited or no support for novel C-ITS safety services majority of which require IP-based communication capabilities often at much higher bandwidths. A connectivity architecture supporting C-ITS safety services should therefore allow for variety of communication types cumulatively referred to as V2X (see Table 2). This is in part due to the fact that the modern vehicles are increasingly being equipped with a wide range of sensors that can contribute to better-informed safety decisions Guerrero-Ibáñez et al. (2018). V2X between road elements enables the use of aggregate sensory information that can significantly improve the safety and help mitigate the risks.

V2X is highly reliant on the underlying wireless technologies, with the most widely-used being DSRC Kenney (2011). DSRC uses 802.11p standard which is an amendment to 802.11 (i.e., Wi-Fi) for WAVE as the physical and media access layer protocol and is suitable for a variety of short-range services used in C-ITS. However, DSRC-based C-ITS inherently suffers from the same symptomatic issues similar to the Wi-Fi networks: (1) poor performance and low reliability in high density and congested areas, where many vehicular transmitters are contending to access the shared channel; (2) being limited in range to a short distance of dozens of meters similarly to 802.11a protocol which it is based upon; and (3) low aggregate bandwidth of 27 Mbps at maximum. Therefore C-ITS approaches purely based on DSRC suffer from scalability issues.

Another proposed alternative is cellular connectivity, often described as C-V2X. In addition to higher aggregate capacity, C-V2X has several advantages over DSRC. However, there is not a "one size fits all" technology for V2X as DSRC has a long history of deployment in the market since late 90's FCC (2020), been constantly improving, and its solutions are considered "ready to roll" by the automotive industry and road authorities. Hence it is realistic to assume that the future V2X ecosystem will include both DSRC and C-V2X and will therefore be heterogeneous. It is expected that the C-V2X deployment will significantly be shaped by the emergence of 5G mobile networks since a major 5G use-case is automotive. 5G is expected to reduce the end-to-end latency among the vehicles and infrastructure down to 1 ms in its URLLC service from tens of milliseconds that are common in 4G networks. This enables a set of new safety services that were otherwise not possible to deploy due to their stringent latency-sensitive requirements such as assisted/cooperative sensing/maneuvering and tele-operated driving Boban et al. (2018).

We highlight our contributions in this paper as following: (1) we provide an overview of safety services and technologies within the road tunnels; (2) offer in-depth insight into the state-of-the-art connectivity for these services; (3) propose an ultra-reliable connectivity architecture based on 5G networks to enable novel C-ITS tunnel safety services. This paper is therefore structured as follows: Section2 provides an overview of road tunnel safety issues, common threats and ICT-based solutions; Section3 presents common and future communication technologies and C-ITS communication paradigms for tunnel safety; Section4 provides an overview of 5G vision and KPIs in particular for vehicular environments and presents our proposed 5G-based connectivity architecture for tunnel safety; and finally Section5 concludes the paper with future works. Further, a list of major acronyms used throughout this paper is brought in Table 1 for the reader's convenience.

2. Tunnel Safety: Threats and ICT-based Solutions

Fire, collisions, and toxic fumes released due to incidents are common threats in tunnels Sun et al. (2019); Qu et al. (2013). Ren et al. (2019) finds that 62% of all tunnel fire accidents in China during 2000–2016 were caused by technical issues in the vehicles – among others by engine or tire fire, or initiated by electric appliance in the vehicle. Further, Melby et al. (2002) identifies that vehicle engine trouble is the cause of 48% of accidents in Norwegian sub-sea tunnels. The notorious 1999 tunnel fire in Mont-Blanc that took 35 lives has been attributed to an engine fire in a heavy-goods vehicle although most of the causalities were due to suffocation from toxic smoke. A common feature of heavy goods vehicle and bus fires inside tunnels is that such fires escalate rapidly Ingason (2015). To mitigate these risks, a set of measures have been commonly taken – e.g., installation of fire-fighting equipment, emergency rooms, SOS telephone lines and ventilation systems. However, automatic detection of incipient incidents can significantly reduce the risks. Early-stage anomaly detection using AIDS is therefore vital.

2.1. *Tunnel AIDS*

AIDS uses sensors to automatically detect an impending incident and take necessary response measures. It has three common types: (1) video-based; (2) inductive loops; and (3) radar-based.

2.1.1. *Video-based AIDS*

Video-based AIDS are very common ViaNova (2013). They rely on common road-side CCTV or dedicated surveillance cameras. Machine learning methods can be used to detect/classify an object type or an anomaly within the tunnel using the video feed. For instance, Dai et al. (2019) surveys a set of fire/smoke VID algorithms based on back-propagation and convolutional neural networks. VID cameras can be functioning in both visible light spectrum as well as infrared (IR). VID systems equipped with dual cameras can help detecting the location of the fire/smoke by providing a stereo vision while an additional IR source can help detecting smoke in dark tunnels. In addition, using signal and image processing techniques several types of anomalies within the tunnel can be detected – e.g., slow/stopped vehicle, vehicles moving in the wrong direction, pedestrians, and sudden reduction in vehicle's speed. VID systems require regular maintenance (e.g., cleaning the lens), and calibration to the operating environment to reduce the number of false-positive signals.

2.1.2. *Inductive loop AIDS*

Insulated inductive loops installed under the road surface use alternating currents to detect passing vehicles and can provide an overview of traffic status in the tunnel. They can either be installed at the entrance/exit or across the entire tunnel length. Dual-loop systems can therefore be used to measure the speed, length and class of the vehicles Gajda et al. (2012). Inductive loops perform accurately in estimating the number of vehicles arriving/departing the tunnel in presence of different lighting conditions and low visibility that VID is prone to. However, most of the incidents need to be indirectly inferred – e.g., detection of fire and smoke ViaNova (2013). They also require the tunnel's closure for maintenance and are expensive to re-install since they are located under the road surface.

2.1.3. *Radar-based AIDS*

Radars installed in the tunnel ceiling, operating at microwave band have been utilized for vehicle classification and speed detection using the Doppler principle – e.g, more commonly in France and Germany PIARC-C5 (2004). They can also be used for detection of pedestrians and other objects but the emergence of smoke and fire needs to be deduced indirectly. One of their main advantage is that unlike VID they are agnostic to the lighting, temperature and visibility conditions, can keep operating in smoke/fire conditions, and are therefore reported to produce less false-positive signals Jensen (2013). Alternatively, other radar-based AIDS are proposed for use that utilize ultrasonic signals instead of microwave but they suffer from signal attenuation and distortion in presence of wind (i.e., air flow), and other environmental factors and also perform poorly in detecting snow-covered vehicles Nikolaev et al. (2017). Further, when used in the tunnels, they are prone to the ambient noise and therefore not recommended PIARC-C5 (2004). Hence, radar-based AIDS in tunnels are mainly focused on microwave band ViaNova (2013).

2.1.4. *Other solutions*

In addition to the above categories other AIDS mechanisms have also been proposed – e.g., non-imaging IR sensors or laser scanners. IR line scanners can be used for anomaly detection such as the heat signature of a vehicle's engine/tires that is about to catch fire, as a prevention mechanism before fire actually begins. Another use-case is to detect and count the number of road users in the tunnel based on human body's IR signature, a vital information during emergency response.

Laser scanners can be complementary to IR sensors in order to construct a 3D model of passing vehicles. This can help with classifying the type and class of passing vehicle and improve the accuracy of AIDS (e.g., mapping a detected heat source to a specific component of a vehicle) Nordnes-Jensen (2019). Such techniques can be accompanied by traditional approaches such as ANPR cameras.

3. Tunnel Communication for Safety

Tunnels are challenging environments for communication. Open air wireless communication do not penetrate deep in tunnels and is mostly accessible only at the entrances. Providing wireless access in the tunnel requires extending the signal coverage by deploying in-tunnel transmitters – e.g., with iDAS or leaky-feeders (i.e., radiating cables). Such transmitters can act as repeaters or use a fibre-optic based backhaul that extends across the tunnel. Further, tunnel walls are reflective and cause signal attenuation and fading in the tunnel.

However, almost all ICT-based solutions mentioned in § 2 require some means of communication. This can be between the in-tunnel RSUs, or from RSUs to a tunnel communication gateway system (e.g., often located in the service rooms, and within a SCADA system) and eventually to the CTC. Further, in the context of C-ITS, RSUs *should* be able to communicate with vehicle's OBUs. Communication requirements in tunnels vary significantly depending on several factors, among which the most intuitive are:

Deployed AID system(s): used AIDS type. For instance VID has a much higher bandwidth requirement than inductive loops.

Tunnel length: defines the density of AIDS sensors/devices per kilometer.

Tunnel vehicle traffic load: often indicates the amount of network traffic generated depending on the measurement method.

Type of communication: communication can be from AIDS to the CTC (or intermediate entities) or to the road user. In C-ITS vehicles are also involved. Table 2 provides an overview of V2X communication types that are common in C-ITS, accompanied with a tunnel safety use-case.

Data content type/volume: most sensors produce little amount of network traffic; however, when aggregated across many sensors deployed in the tunnel and over time/distance, data volume can become significant. Although transferring 24/7 live video feeds from many cameras require high bandwidth links, VID systems that rely on transferring only in presence of a detected anomaly, reduce this requirement significantly. Some data do not necessary need to be sent in real-time while others can be latency-sensitive. An example of latency-sensitive communication is cooperative maneuvering in C-ITS.

Table 1. Acronyms used in this paper.

Acronym	Title
3GPP	3rd Generation Partnership Project
AIDS	Automatic Incident Detection Systems
ANPR	Automatic Number Plate Recognition
C-ITS	Cooperative Intelligent Transport Systems
CACC	Cooperative Adaptive Cruise Control
CAPEX	Capital Expenditure
CTC	Central Traffic Control
DAB	Digital Radio Broadcasting
DGV	Dangerous-Goods Vehicle
DSRC	Dedicated Short-Range Communications
eMBB	enhanced Mobile BroadBand
ICT	Information and Communications Technology
iDAS	indoor Distributed Antenna Systems
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LPWAN	Low Power Wide Area Network
MEC	Multi-access Edge Computing
mMTC	massive Machine Type Communication
MNO	Mobile Network Operator
NB-IoT	Narrow-Band IoT
NFV	Network Function Virtualization
OBU	On-Board Unit
OPEX	Operating Expense
PoE	Power-over-Ethernet
RSU	Road-Side Unit
SCADA	Supervisory Control and Data Acquisition
Tetra	Terrestrial Trunked Radio
URLLC	Ultra-Reliable Low Latency
V2X	Vehicle-to-Everything communication
VEC	Vehicular Edge Computing
VID	Video Image Detection
WAVE	Wireless Access in Vehicular Environments

Next, we provide an overview of the communication technologies that are commonly used or being considered for future use in tunnels.

3.1. *Communication Technologies in Road Tunnels*

Existing road tunnel communication technologies can be divided into three major categories: (1) audio-based radio; (2) wired backhaul; and (3) wireless on the access links.

3.1.1. *Audio-based radio*

Traditional road safety emergency response has relied on audio-based radio services. This includes broadcasting safety information on DAB+ ETSI (2020a). DAB+ repeaters installed in the tunnels allow for a break-in functionality where all regular broadcasts are interrupted and instead a safety message is transmitted on all channels. While DAB+ is meant purely for audio broadcast, DAB-IP allows for transmission over IP data network. There are also proposals for using IP data over DAB Morgner and Stauber (2016). However such solutions are limited in bandwidth and are not supported by legacy in-vehicle DAB receivers and are thus not scalable.

Another audio-based radio intended as emergency dispatch service is Tetra ETSI (2020b), the European counterpart of North American P25 (APCO) (2020). Unlike broadcasting service provided by DAB+, Tetra provides a two-way communication at the very low rate of few kbps sufficient enough to deliver dispatch services. Similarly to DAB+, Tetra coverage can be extended in tunnels. For instance, in Norway which has the highest number of tunnels-per-capita, Tetra-based Nødnett already covers more than 390 tunnels which includes all tunnels longer than 500 m with the daily traffic exceeding 5k vehicles nod (2020).

3.1.2. *Wired backhaul*

Ethernet-based fibre optics have been commonly used as communication backhaul in tunnels connecting a large variety of devices to the CTC within an SCADA system. To ensure highly reliability and fault-tolerance in case of structural damage, a ring system network architecture is often used based on ITU G.8032 specifications (ITU) (2020). Such network would be connected using industrial PoE switches that are located in service rooms. The use of PoE would mitigate the need for extra wiring for power.

3.1.3. *Wireless on the access links*

Currently last-hop wireless access in tunnels is mostly aimed at cellular mobile coverage (e.g., 3G/4G). This coverage varies significantly depending on the country, length, traffic level, location and other factors. As a rule-of-thumb road tunnels in urban areas, or those connecting major highways are more likely to have cellular coverage than other tunnels. Also, subway tunnels in metropolitan areas are likelier to be covered than others. It is anticipated that cellular coverage in tunnels will increase significantly with the emergence of 5G mobile networks.

In addition, sensor devices in tunnels (e.g., AIDS) might use a variety of IoT-based com-

Table 2. C-ITS V2X communication paradigms.

Name	Type	Tunnel Safety Use-case
V2V	Vehicle to Vehicle	CACC with automatic distance adjustment based on feedback from a DGV ahead.
V2I	Vehicle to Infrastructure	ACC based on feedback from tunnel AIDS/RSUs about detected anomaly on a DGV ahead.
V2P	Vehicle to Pedestrian	Vehicle sends safety alerts and information to pedestrians in the tunnel based on its local sensing and received data from infrastructure or CTC.
V2N	Vehicle to Network	Vehicle receives detailed updates on tunnel status from CTC on its infotainment system and also shares its data (e.g., vehicle's engine status, etc.)

munication technologies, mostly within the LPWAN category due to the lengthiness of road tunnels. An example of LPWAN is LoRaWAN Bor et al. (2016) that is employed in particular during the construction phase –e.g., in the Grand Paris Metro project iot now (2020). However, LoRaWAN offers a very limited bandwidth of 27 kbps at maximum with strict link budget allocation, hence making its applicability limited to very resource-constrained and delay-tolerant IoT devices. On the other hand, cellular-based IoT has been considered as an alternative for LoRaWAN – e.g., NB-IoT, and LTE-M for MTC that are standardized by 3GPP 3GPP (2020). While NB-IoT can offer data rates in orders of 10s$\sim$100s of kbps, LTE-M provides a higher data rate of several Mbps albeit at a higher price-per-unit.

In addition to these, Wi-Fi is also considered as another form of connectivity in tunnels. Wi-Fi signal operating in 2.4 GHz and 5 GHz bands is much more prone to signal attenuation and fading than cellular LTE that normally uses lower bands. In order to mitigate this issue, circular polarization instead of linear on Wi-Fi antennas have been proposed using high-rotating beams that provide an extended range for Wi-Fi signal Ridge (2020).

Another type of wireless access is intended for V2X, enabling a variety of novel C-ITS services including for safety. There are two main V2X technologies; DSRC FCC (2020) and C-V2X that commonly share the market. DSRC and its product ecosystem precede the more recently rising C-V2X. For example, most currently deployed automatic road/tunnel tolling systems are DSRC-based. It is therefore expected that both technologies share the ecosystem in coming years while C-V2X is likely to take over in mid-2030's. This projection is mainly attributed to the emergence of 5G networks, its significantly higher bandwidth, and its new architectural design which we will elaborate further on in § 4.

3.2. *C-ITS use-cases for road tunnel safety*

Novel C-ITS solutions can be employed for road tunnel safety as shown with few examples in Table 2. For instance, Chen et al. (2015) lays out and compares different coordination approaches for maintaining distance between DGVs and other vehicles. In addition, a joint work by two industry stakeholders CohdaWireless and Aventi demonstrated V2X for C-ITS applications in tunnels CohdaWireless (2020). Boban et al. (2018) presents a set of C-ITS use-cases such as cooperative maneuvering, sensing, and awareness as well as teleoperated driving in the context of road networks. Specific tunnel safety scenarios can be applied to each of these use-cases. For example, using CACC, the distance between DGV and other vehicles can be automatically adjusted. This can be done either with V2V communication if the DGV is already equipped with V2X functionality or through V2I communication from an AIDS or even V2N from CTC. The ability to use multiple V2X modes facilitates the gradual deployment of the C-ITS system where some of the vehicles are yet to be equipped with V2X functionality. This paper does not aim to provide an exhaustive list of possible C-ITS tunnel safety applications but rather highlights the relevance between the tunnel safety with C-ITS, V2X and underlying wireless technology. Detailed lists of C-ITS scenarios are brought in 3GPP (2019).

4. 5G Communication Architecture for Tunnel Safety

This section presents our proposed 5G-based connectivity architecture for road tunnel safety. First, we provide an overview of 5G, its vision and conceptual paradigms as well as 5G-V2X and then lay out our proposed architecture.

4.1. *IMT-2020 5G vision*

ITU's Radio-communication sector (ITU-R) has specified a roadmap vision for future 5G mobile networks, which will lead to the development of a new set of standards referred to collectively as IMT-2020. The requirements set in the IMT-2020 will push the boundaries of KPIs currently provided by 4G networks significantly as laid out in ITU-R M.2083-0 ITU (2015). As captured in Table 3, most KPI requirements will be increased by at least an order of magnitude in comparison with IMT-Advanced (4G). IMT-2020 also defines three major 5G use-cases: (1) eMBB; (2) URLLC; and (3) mMTC. Each of these use-cases correspond to a set of applications. For instance, eMBB consists of the common mobile broadband applications such as HD video-streaming and Internet surfing, while URLLC is aimed at mobility, automotive and mission critical applications that require very low radio latency. On the other hand, mMTC supports a large number of IoT devices (e.g., in industry 4.0). In particular, URLLC is expected to serve the future C-ITS applications using 5G C-V2X. One of the major challenges of deploying C-ITS on public roads particularly in scenarios such as real-time cooperative maneuvering, CACC, and tele-operated driving has been the lack of ultra-reliable and low latency wireless communication both for V2V and V2I communications due to intrinsic unreliable nature of most wireless technologies such as DSRC. Ensuring URLLC in 5G will allow for rolling out such latency-sensitive C-ITS applications. 5G standards are currently being developed by 3GPP (2020).

Table 3. ITU's IMT-2020 5G KPI requirements and improvement factor (IF) compared to IMT-Advanced (4G).

KPI	**Value**	**5G use-case**	**IF**
Peak data rate	20 Gbps	eMBB	20x
User experienced data rate	100 Mbps	eMBB	10x
Latency	1 ms	URLLC	10x
Mobility	500 km/h	eMBB & URLLC	$\sim$1.4x
Area traffic capacity	10 Mbps/m^2	eMBB	100x
Connection density	$10^6/km^2$	mMTC	10x

4.2. *Network Slicing and NFV in 5G*

Traditional networks has thus far been following the "*one size fits all*" service architecture principle. This is no longer viable for today's applications that often have vastly different and specific performance requirements. For instance, in order to maximize their revenue, different industry verticals might be interested in tailoring these requirements according to the specific needs of their customers, ranging from IoT and industry 4.0 to AR/VR and automotive, etc. This means, it is no longer possible to satisfy the customized KPIs of such verticals in a single network service setup.

To ensure service requirements of each vertical, *network slicing* concept can be implemented by MNOs. A network slice can be perceived as an independent *virtual* network that runs over a shared physical resource in end-to-end fashion GSMA (2018). Network slicing is an essential part of 5G architecture and is a bold departure from 4G design. It relies heavily on NFV which allows for consolidating many network hardware types specific to one network function (e.g. routing/switching, firewall) into general commodity hardware that can run any network functionality in a virtualized environment, hence reducing the OPEX/CAPEX of MNOs and other industry verticals Virtualisation (2012). A major benefit of network slicing is *network isolation* in terms of fault, security, performance and management.

In automotive, different slicing strategies can be adopted. As a general rule, three slices can be defined according to three 5G usage scenarios for eMBB, URLLC and mMTC services. This allows C-ITS tunnel safety applications to run on a dedicated URLLC slice with isolation from general Internet surfing and infotainment traffic. Consequently, URLLC slice can be treated differently than other slices, e.g., with higher traffic priority, quality of service and resource scheduling based on upcoming 3GPP specifications for URLLC service as well as customized tunnel safety requirements. Figure 1 shows a sample 5G network slicing model for such scenario. It is worth noting that more slices can be added to this model based on specific tunnel safety requirements.

4.3. *5G VEC*

VEC is a form of MEC intended for vehicular communication Liu et al. (2019). MEC allows to offload computational and storage tasks from cloud-based backend to the edge server and hence reducing the load and traffic on the cloud and improving the end-to-end latency and response-time. In VEC, automotive applications could be hosted on the edge (e.g., on/near RSUs) in a virtualized environment which would improve the performance of real-time C-ITS applications including safety apps (see Figure 1). Virtual VEC server instances could be served by different network slices according to their KPI requirements. A major advantage of using virtualized VEC is the ability to define and deploy new services in a matter of weeks instead of years. At the moment, tunnel safety applications are hard and time-taking to deploy and upgrade as they are highly reliant of vendor/function-specific solutions. With VEC, deploying or upgrading a new safety application would be ideally as easy as initiating a new or updated virtual instance in the VEC servers (i.e., copying a file by a command from CTC).

4.4. *5G Communication Architecture for Tunnel Safety*

Based on what we have laid out so far, we provide a conceptual model of our proposed 5G connectivity architecture for tunnel safety as depicted in Figure 2. To ensure high reliability and low-latency for C-ITS safety applications, they are assigned to a dedicated network slice (URLLC slice, or slice #2 of Figure 1) in order to provide isolation from the rest of network traffic. Only latency- and mission-critical applications (e.g., V2X indoor positioning) would share the slice with safety applications. Network and resource scheduling will be performed using NFV in such a way that URLLC slice will have the highest priority in the end-to-end network. Further, in order to minimize the latency and distribute the load, VEC servers will host C-ITS safety applications on the edge reducing the round-trip time further significantly. The AIDS can communicate with VEC-hosted applications directly and/or to the CTC and cloud-based backend depending on the application requirements. New or upgraded safety applications can be pushed to the virtual instances in VECs from CTC frequently reducing the deployment and upgrade time drastically. For V2V, LTE-sidelink (PC5) Molina-Masegosa and Gozalvez (2017) or DSRC can be used depending on the specific application requirements.

4.5. *Cybersecurity Implications*

As C-ITS becomes more prevalent, road infrastructure can become one of the prime targets of cyber-attacks and it is therefore essential that tunnel safety communication is highly secured. In this context, deploying 5G-based solutions will have several implications mostly due to softwarization and distributed nature of many functionalities that were traditionally physically managed within fixed points. Unlike static cybersecurity policies, presence of dynamic network slices offering various services require introduction of dynamic policies tailored to the cybersecurity risks/threats within each slice. Secondly, NFV introduces new security challenges due to potential malicious exploitation of network configuration which can be amplified because of NFV's flexible nature. On the other hand, such flexibility can help to reduce the incident response time Lal et al. (2017). A detailed exploration of 5G cybersecurity threats and mitigation strategies are out of the scope of this paper.

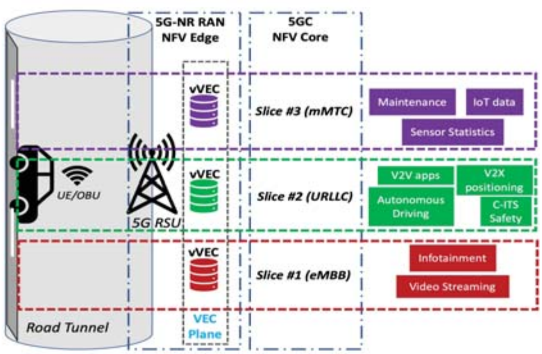

Fig. 1. A sample 5G network slicing model for C-ITS tunnel safety.

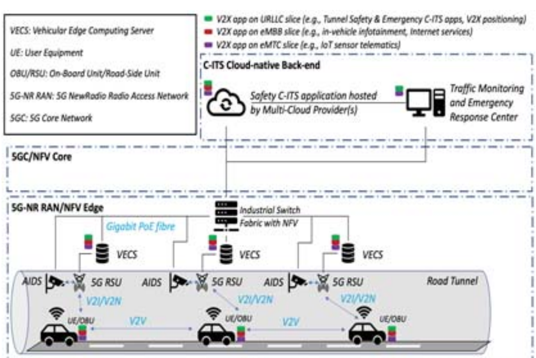

Fig. 2. 5G-based ultra-reliable and low latency network architecture model for tunnel safety communication.

5. Conclusive Remarks

In this paper we provided an overview of risks within the road tunnels and offered a detailed insight into common tunnel safety services and AIDS technologies. We also laid out an overview of communication technologies used for tunnel safety with a highlighted focus on V2X and C-ITS services. In order to provide a connectivity architecture that meets the ever-increasing demand of C-ITS applications (e.g., low latency, high reliability and/or bandwidth), and services particularly in the context of road tunnel safety and emergency response, we proposed an ultra-reliable connectivity architecture based on emerging 5G mobile networks that takes advantage of VEC, NFV and network slicing, inherent to 5G design. While VEC allows for faster response time, NFV and network slicing allow for ensuring the KPI requirements of tunnel safety services within the network through end-to-end isolation by virtualization. Further, such virtualization allows for reducing the deployment time and cost of novel C-ITS safety services in tunnels significantly.

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