Product analysis of a Wi-Fi based platform for vehicle connectivity

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Master's Dissertation

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Mestrado Integrado em Engenharia e Gestão Industrial

2020-02-04

Abstract

The car of the future is going to be silent and with low emissions, due to its electrification, and mobility is moving to new models based on mobility as a service and shared mobility, that will be cheaper and more accessible due to the absence of initial investment. Mobility will be both safer and revised as experience since less will be expected from the driver. However, with considerable changes and disruptions come also essential requirements, and the one thing in common that all of these will need is data, and connection to all the relevant nodes surrounding the vehicles, from road infrastructure and the internet network to other vehicles and pedestrians.

This is where the "Internet of Moving Things" comes into the spotlight as the first step into the future of mobility. Veniam understood that trend early on, and for the past eight years has been working on delivering the network fabric for the internet of moving things. Despite the recent developments in technologies around the cellular broadband technologies, more specifically in 5G and C-V2X, and the ones already introduced in the past decades, namely on Dedicated Short Range Communications (DSRC), the industry is yet to have a clear direction how the vehicles will communicate, and having the needed infrastructure to support it. Currently, vehicles are entirely dependent on the available broadband technologies, 4G and 3G, which are expensive, occasionally unavailable, and limited to internet connectivity. Veniam detected that Wi-Fi, a widely available and with a mostly underused capacity, could be used for such purposes, despite the lack of research and material on how to make use oh Wi-Fi to connect vehicles.

The product developed has as foundations the Wi-Fi protocols, and it was recently ready as a prototype to be tested and analysed. In this dissertation, an extensive product analysis is made, testing the product at its full capacity in various ways, and compared to the remaining technologies. In pursuance of this analysis, a literature review approaching the leading available technologies for vehicle connectivity, Wi-Fi, cellular broadband technologies, DSRC and C-V2X, was performed, followed by a market analysis aiming to bring light to the current trends, needs and requirements both from the end-customers and the OEMs. Those were translated into concrete applications and use cases, that were divided based on their delay tolerance. A survey on the Wi-Fi availability and the prices for each technology were presented, along with a short technical explanation on how Wi-Fi could be used to connect vehicles. With the foundations set for the assessment of the described technology, two tests were defined and performed.

The results obtained were used to evaluate the solution, and the conclusions were promising, suggesting that this technology is suitable to fulfil the delay-tolerant cases, and even some real-time, delay intolerant applications. Some high dependencies on the geographies as well as the routes chosen, and the driving behaviour were also seen. Since C-V2X and DSRC are still to come as a comprehensive solution, and Wi-Fi is cheaper than the available alternatives, what came to be as an attractive hypothesis is the usage of multiple technologies for vehicle connectivity. Additional investigations and further work are proposed. This thesis makes clear that Wi-Fi should not be ignored when discussing how vehicles can communicate with all the other nodes in the future of mobility.

Resumo

O veículo do futuro será elétrico, e como tal, será caracterizada pelas baixas emissões de CO2 e menor ruído. Estes veículos elétricos serão também partilhados e autónomos, o que está a conduzir a indústria para novos modelos de negócio, baseados em serviços, que serão mais económicos e acessíveis devido à ausência de um investimento inicial e a partilha terá um efeito de diluição do custo total da posse. A mobilidade será mais segura e as experiências no interior do veículo serão redefinidas, uma vez que dependerá cada vez menos das ações por parte do condutor. No entanto, estas mudanças trazem também novos desafios e requisitos críticos, e neste caso, a necessidade transversal à troca de informação e a conectividade entre os veículos e todos os elementos envolvidos no processo de mobilidade (como a infra-estrutura rodoviária, a rede de Internet ou mesmo outros veículos e peões).

É aqui que a "Internet of Moving Things" entra em foco como o primeiro passo para o futuro da mobilidade. A Veniam detetou essa tendência desde cedo e, nos últimos oito anos tem vindo a trabalhar na construção da rede para as coisas em movimento. Apesar dos recentes desenvolvimentos em torno das tecnologias de banda larga celular, mais especificamente em 5G e C-V2X, e das já introduzidas nas últimas décadas, nomeadamente as Comunicações Dedicadas de Curto Alcance (DSRC), a indústria ainda não tem uma direção clara sobre como os veículos irão comunicar, e a infra-estrutura necessária para a suportar. Atualmente, os veículos estão totalmente dependentes das tecnologias de banda larga disponíveis, 4G e 3G, que são caras, ocasionalmente indisponíveis e limitadas à conectividade com a Internet. A Veniam verificou que Wi-Fi, uma tecnologia amplamente disponível e com uma capacidade maioritariamente subutilizada, poderia ser utilizado para tais fins, apesar da falta de pesquisa e material sobre como utilizá-lo para conectar veículos.

O produto desenvolvido pela Veniam tem como base os protocolos Wi-Fi, sendo que foi recentemente finalizado como um protótipo para ser testado e analisado. Nesta dissertação é feita uma análise do produto, testando a sua capacidade e comparando-o com as restantes tecnologias. Foi realizada uma revisão bibliográfica abordando as principais tecnologias disponíveis para conectividade automóvel; Wi-Fi, tecnologias de banda larga celular, DSRC e C-V2X, seguida de uma análise de mercado com o objetivo de identificar as tendências, necessidades e requisitos actuais, tanto dos clientes finais como das produtoras automóveis. Estas necessidades foram traduzidas em aplicações e casos de uso concretos, que foram divididos com base na sua tolerância a atrasos. Foi apresentada uma pesquisa sobre a disponibilidade de Wi-Fi e os preços de cada tecnologia, juntamente com uma breve explicação técnica sobre como o Wi-Fi poderia ser utilizado para conectar veículos. Com as bases estabelecidas para a avaliação da tecnologia descrita, foram definidos e realizados dois testes.

Os resultados obtidos foram utilizados para avaliar a solução, e as conclusões foram promissoras, sugerindo que esta tecnologia é adequada para atender aos casos tolerantes a atraso, e até mesmo algumas aplicações intolerantes a atrasos, de tempo real. Também foram observadas possíveis dependências das geografias, bem como das rotas escolhidas, e o comportamento de condução. Uma vez que C-V2X e DSRC estão ainda indisponíveis como solução viável pronta a utilizar, e sendo Wi-Fi mais barato e mais rápido que as alternativas disponíveis, o uso de Wi-Fi juntamente com as restantes mostra-se como hipótese apelativa a ser analisada. São propostas investigações adicionais e possível trabalhos futuros. Esta tese deixa claro que o Wi-Fi não deve ser ignorado quando se discute como os veículos podem comunicar no futuro da mobilidade.

Acknowledgments

I have been blessed throughout my life to be surrounded with outstanding people, that not only inspired and pushed me to be the best version of myself but always provided me with all the support, strength and conditions for success.

I would like to start by appreciating to what was my like second home, FEUP, and its community. More than a university, it is a school of thought and an incubator for opportunities, but also a place with memories of laughter, developing grit, realising the power of teamwork, and how to truly learn. Besides the academic knowledge provided, it was the platform for the best opportunities and a safe place to start defining myself.

To Veniam for providing me with this project as well as the opportunity to get to know its operations, be part of its daily activities, and experiencing first hand the work of a product team member. From the first day, I was welcomed with open arms, and the support for this project was far greater than I ever imagined. And especially, I would like to thank Caspar Vogel, André Cardote for all their support and help as my supervisors, as well as all those who helped and guided me through the course of this project. And to Darija; a great friend before a colleague.

To the greatest gift that the university has awarded me, the most fantastic group of friends and companions to this adventure. Without their constant challenges and support, that has prevailed even after our academic life, I would have never taken so much out of these years, from knowledge and lessons to the most significant memories and moments that I cherish so much. I take these friendships for life.

My friends that have been with me for life that shaped me since a young age into what I am now and that were there throughout all my adventures and developments, despite how challenging it was sometimes. I would not be who I am without you.

But the most enriching experience of not only my academic life is undoubtedly among ESTIEM. There I have not only known myself to points I never imagined and my limits but people who inspired and changed me. Diogo, Joonas, Minh, Yassine and Sunny; the most outstanding group of people I had the privilege of working with. You showed me how real friendship can enhance the quality and experience of working. You saw me at my worst and my best, and you greatly improved my best.

To my family: my loving parents and my amazing sisters, who have taught me the meaning of unconditional love and support, always there to encourage me in my out of the box ideas, and to push me further when in moments of doubts, even when it was hard for them. Since the beginning of my life, they were there to catch my tears and in the first row to celebrate my success. You are my safe harbour and founding pillar of my life. And more than anyone, you made me get where I am today. I owe every single thing to you.

Lastly and foremost, to Yassine. The best companion, challenger and supporter I could have asked for. I hope never to stop learning with you and growing together.

Thank you. My success is yours.

"Life requires movement."

Aristotle

Contents

Acronyms and Symbols

3GPP	Third Generation Partnership Project
5GAA	5G Automotive Association
ABS	Anti-lock braking System
AI	Artificial Intelligence
AV	Autonomous Vehicles
CASE	Connected, Autonomous, Shared, Electrical Vehicles
CEN	European Committee for Standardisation
CTO	Chief Technology Officer
C-ITS	Cooperative Intelligent Transport Systems
DDT	Dynamic Driving Tasks
DHCP	Dynamic Host Configuration Protocol
DSRC	Dedicated Short Range Communications
DSSS	Direct Sequence Spread Spectrum
EAP	Extensible Authentication Protocol
EU	European Union
EV	Electric Vehicle
FCC	Federal Communications Commission
FHSS	Frequency-Hopping Spread Spectrum
IEEE	Institute of Electrical and Electronics Engineering
IMT	International Mobile Telecommunications
IP	Internet Protocol Address
ITU	International Telecommunication Union
LTE	Long Term Evolution
MaaS	Mobility as a Service
MIMO	Multiple Input Multiple Output
MU-MIMO	Multi User Multiple Input Multiple Output
NHTSA	National Highway Traffic Safety Administration
NOC	Network Operations Centre
NR	New Radio
OBU	On Board Unit
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OTA	Over The Air
PSK	Pre Shared Key
QoS	Quality of Service
RAT	Radio Access Technologies
RSU	Road Side Unit

SAE	Society of Automotive Engineers
SISO	Single Input Single Output
SSID	Service Set Identifier
STCP	Sociedade de Transportes Colectivos do Porto
TCP	Transmission Control Protocol
USA	United States of America
VANET	Vehicular ad hoc network
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VR	Virtual Reality
WAVE	Wireless access in vehicular environments
WBA	Wireless Broadband Alliance
WISPr	Wireless Internet Service Provider Roaming
WLAN	Wireless Local Area Network
WPA	Wireless Access Protocol

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Chapter 1

Introduction

The present chapter aims to provide an introduction to this dissertation, starting by exposing the motivation that leads to the project undertaken in Section 1.1, followed by a short introduction to the company in Section 1.2 and a brief description of the topic of the present dissertation in Section 1.3.

1.1 Motivation

The automotive industry is moving to a direction where vehicles are no longer isolated devices, but alternatively, connected machines with the environment they integrate. Cars are increasingly expected to be able to communicate with other nodes, such as the cloud, other vehicles or infrastructure surrounding them. This is where Veniam comes into play: a platform for the Internet of Moving Things.

The market is predicted to have all new cars produced from 2022 as connected devices, and therefore, a need arises in the market to enable and manage the connection of the vehicles. A wide range of technologies equips the industry to support connectivity in vehicles, but in order to maximise value, it is crucial to make the most out of all the available knowledge and resources at hand and bring it to the new levels of utility and excellence.

Veniam's solution utilises the infrastructure already installed in locations all over the world, Wi-Fi routers, and the hardware that already integrates most of the connected vehicles, on-board units, to establish connections to the network through Wi-Fi quickly, and between vehicles, as well as road infrastructures using those same channels.

During the past seven years, Veniam has been consistently proving the concept of its product by developing solutions for ports, bus fleets, taxis and other vehicles, operating mesh networks in New York, Singapore and Porto, with Porto being the first and largest vehicular mesh network. Now, with over one million kilometres of Vehicle to Everything (V2X) mesh connected vehicle data and 15 terabits of data transferred monthly, Veniam is entirely investing its efforts on working with automotive Original Equipment Manufacturers (OEMs), Tier 1 suppliers and other technology companies to provide the intelligent networking platform for connected cars and autonomous vehicles.

Due to the uncertainty around the concrete future of mobility, its subsequent requirements, and the fast-changing landscape, it is a challenge for the academic and scientific world to have an up-to-date state-of-the-art description of the environment. Thus, having a good snapshot of the market tendencies and trends at any point in time becomes a challenge and vital for success. It is, therefore, of the utmost importance to identify and outline the direction of the market, and ensure that Veniam's product fulfils the market needs, both as it is today, and how it will come to grow in the upcoming years.

1.2 Veniam

Veniam is a technology start-up born in 2012 with the foundations on the work of João Barros, Susana Sargento and their research teams, in the University of Aveiro, University of Porto and the Portuguese Telecommunications Institute. As a result of their academic research, they built the first real-world testbed of connected vehicles, with 60 taxis in Porto. When the outside world showed interest in their project, they started grasping the value that vehicular mesh networks could have in the future. João and Susana were later joined by the Robin Chase and Roy Russel, founders of Zipcar. Since then, that project has raised more than $30 million in Venture capital-backed by both Venture Capital and Market leaders such as Verizon, Cisco, Orange, Liberty Global, and Yamaha Motors. Furthermore, Veniam won several awards such as CNBC Disruptor 50, TU Automotive Best mobility Product and CableLabs® Innovation Showcase for Most Innovative Product Award.

Veniam's product is, therefore, a platform that performs a smart (and local) data management, moving data between the vehicle and the cloud using multi-network architectures and technologies such as Wi-Fi, cellular data and Dedicated Short-Range Communication (DSRC). It is a safe and low latency network platform that provides scalability and reliability to the customers, and a superior quality of experience to the end-users.

The Veniam platform, illustrated on Figure 1.1, can be seen as having four main components. The connection management component, responsible for achieving maximum connectivity time and quality. The data management component, responsible for distributing the available networking and computing resources by the individual requirements of the vehicle. The policy management functionality that allows customers to set global policies at a cloud level that is easily and automatically applied in the vehicles. Lastly, the provider management that ensures the vehicles to have the appropriate network configurations and credentials to access the relevant access points when needed.

Veniam has currently offices in Mountain View, United States, and in Porto, Portugal, with most of the personnel based in Porto. The functional areas are Engineering, System Operations, Finance, and Product Development.

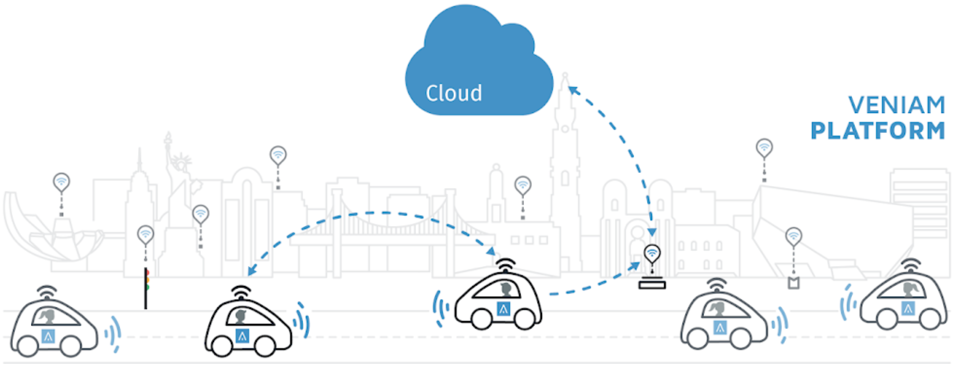


Figure 1.1: Veniam enables applications and services to access the vehicle's data, communications and computing resources with the right Quality of Service and security).

With its name derived from Latin Veniam, which stands for "I will come" or "let me come", used by the Carthaginian general Hannibal Barca in the famous quote "Inveniam viam aut faciam" meaning "I will find a way (road), or I will make one", the name could not suit better a company committed to paving the way for the future of mobility.

1.3 Project scope and objectives

As a consequence of being positioned in a timeline between the present automotive market needs and the future of mobility, Veniam faces added challenges when assessing or presenting the product to the industry. In this context, the present dissertation aims to answer the following question: is the Veniam platform the response to the vehicle connectivity needs required by both the end-customers and the major industry stakeholders?

The academia and the industry do not provide the needed information openly even to define the requirements and needs relating to the applications and connectivity goals, despite the speculation existing in blogs and news all over the world. The technological environment is quickly changing and presenting ambitious projects that aspire to connect vehicles not only to the network but to all objects and mobility stakeholders that interact with the vehicles to make mobility safer, better and environmentally friendly. This thesis aims to perform an extensive product analysis, tackling both the features and the capacity of the product and comparing it with the available alternatives.

1.4 Dissertation Structure

This dissertation is divided into six chapters, where the present chapter was an introduction to the project and the company where it took place.

Chapter 2 presents a literature review on the available connectivity technologies, Wi-Fi, Broadband Cellular Network Technologies, DSRC and C-V2X, and a wrapped up overview of how they compare to each other.

Chapter 3 provides an industry analysis on vehicle connectivity and the inherent needs, a market analysis on the prices for each solution, followed by a study on Wi-Fi and how it is used to connect vehicles.

In Chapter 4, the methodology used for tackling the proposed objectives is described, together with the definition of the criteria for the evaluation of the results obtained. The first section tackles the tests performed and the test environment, while the second section details the analysis of the data from the tests. This is followed by a comparison of the costs of the technologies.

Chapter 5 contains the results obtained by the usage of the methodology described in the previous chapter as well as a first comparison against the set criteria.

As a conclusion of this dissertation, Chapter 6 begins with the discussion of the main findings and the associated implications, as well as some recommendations for the future, academically and in practice, for Veniam. In this chapter, an alternative solution is presented as what could be the best solution for vehicle connectivity.

Chapter 2

Literature Review

The increasing number of people and goods requiring ubiquitous mobility and the subsequent increase negative impact in society such as traffic congestion, fatalities, injuries and inefficient transportation systems, instigated a heavy investment on new solutions to create an intelligent transportation system (ITS). Propelled by the recent development in technologies around computing, wireless communications and hardware, these intelligent systems have been pushed even further, providing the needed foundations to make vehicles safer, more coordinated and smarter. The European Parliament and the Council of the European Union (2010) define ITS as being "advanced applications which without embodying intelligence as such aim to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer more coordinated and "smarter" use of transport networks.".

Connectivity arises as a primary requirement for intelligent transportation systems, as well as for the future of mobility going through autonomous, shared solutions. Vehicles are expected to act as sensors of the environment around them and information related to themselves, and exchange information with other vehicles, users, the infrastructure and the cloud.

This chapter begins with the description and analysis of the most proliferated technologies for inter-vehicle connectivity: Wi-Fi, Cellular broadband network technologies, WAVE/DSRC and C-V2X. A further comparison of these available technologies is made, according to their characteristics, concerns and advantages. The coexistence of the different wireless technologies in various networking techniques is delved into as a summary.

2.1 Vehicle Connectivity

Having established the importance of how vehicles interact with the exterior and connect to others and the internet, it is paramount to describe how this is currently happening and how it will happen in the future.

When discussing Vehicle connectivity, several vehicular communication systems should be considered, together with the inherent requirements.

Vehicle to Infrastructure (V2I) communications consist of the exchange of information and data with the road infrastructure surrounding the vehicles. Examples of road infrastructure include traffic lights, lane markings, road side units (RSUs), and tolls. The applications of such communications are based, for the most part, in safety and traffic management. However, some of the use cases include services and infotainment information broadcasting, such as local attractions advertisement. Since most of the road infrastructure is not equipped for wireless communication, V2I has inherently associated substantial investments by the governments on hardware (Emmelmann et al., 2010).

Vehicle to Vehicle (V2V) encompasses all the communications between vehicles. These were envisioned to enable the vehicles to communicate mainly safety information, including sudden braking, obstacles in the road and other warnings that can be relayed to approaching vehicles. However, some other usages were explored, including content distribution. The main requirement for V2V communications is the allocation of dedicated bandwidth for these communications, another factor dependent on governments. V2V also faces the obstacle of depending on a significant number of vehicles equipped with this capacity to fully grasp the advantages of such technology (Emmelmann et al., 2010). Presently V2V communications are possible through DSRC and C-V2X, explored in the following sections.

Vehicle to Cloud (V2C) consists of the exchange of information between the vehicle and cloud systems. By connecting to the cloud, vehicles can integrate IoT environments. This communication channel is particularly essential for content distribution, such as updates, and for data purposes, some of which are related to data collection for uses such as predictive maintenance, usage-based insurance, and research and development applications, but also to cloud streaming services, such as Spotify, and ubiquitous internet connectivity. In cellular environments, the access to the cloud through cellular infrastructure for non-critical applications is referred to as Vehicle to Network (V2N), when this should, however, be interpreted as equivalent to V2C.

Vehicle to Pedestrian (V2P) serve mainly for safety purposes, as it focuses on the detection of Vulnerable Road Users including Pedestrians, cyclist and motorised two-wheelers. The complexity in V2P is due to the diversity in the characteristics and behaviours of these users. In most architectures, Pedestrians' devices, such as smartphones, are used as sensors and broadcasters of information and data.

Vehicle to Device (V2D) communication is undoubtedly the most common and well established in the automotive industry, where vehicles are able to connect with other electronic devices. Car sharing is heavily dependent on the ability of vehicles to connect to other devices. Examples include keyless vehicles, vehicles connected to smartphones and mobile phones.

Vehicle to Grid (V2G) applies to the electric vehicles, where to charge the vehicle it is required to connect to the power grid to request electricity.

Vehicle to Everything (V2X), enveloping all the systems mentioned above, refers to the ability of vehicles to connect to any entity that might interact with it. V2X communications are expected to make the most out of the environments to establish high-bandwidth, fast, reliable connections, supporting future applications and associated requirements. DSRC/WAVE and C-V2X are the

Table 2.1: Examples of performance requirements for the various communication systems. Source: Boban et al. (2018)

Use Case Type	**Communication System**	**End-to-End Latency**	**Reliability**	**Data Rate per Vehicle (kb/s)**	**Communication Range**
Cooperative awareness	V2V or V2I	100 ms	90-95%	5 - 96	Short to medium
Cooperative sensing	V2V or V2I	3 ms	>95%	5 - 25,000	Short
Cooperative maneuvers	V2V or V2I	<3-100 ms	>99%	10 - 5,000	Short to Medium
Vulnerable Road User	V2P	100 ms	95%	5-10	Short
Traffic efficiency	V2C or V2I	>1 s	<90%	10 - 2,000	Long
Teleoperated driving	V2C	5-20 ms	>99%	>25,000	Long

most significant technologies connecting V2I, V2V and V2C communications systems. However, the implementation of V2X technologies on a significant scale is yet to be observed in the industry.

In Table 2.1, it is possible to observe some examples of the performance requirements for each communication system.

Due to the focus of this dissertation, only technologies enabling V2I, V2V, V2C and V2X will be explored in the further sections. For this purpose, we consider inter-vehicle based communications, such as Dedicated Short Range Communications and C-V2X, and Internet connectivity, such as Wi-Fi and Cellular broadband network technologies. These technologies are delved into more detail in the following sections.

2.2 Wi-Fi

Wi-Fi refers to the wireless communications technology trademarked by the Wi-Fi Alliance (2019), a non-profit worldwide network of companies that aims to connect the world by driving the adoption and evolution of Wi-Fi globally. Wi-Fi technology is based on the IEEE standard 802.11 for wireless communication. IEEE 802 is the family of standards defining the data link and physical layers for local and metropolitan area networks, that includes the foundations for Ethernet and Wi-Fi technologies, and it is widely used worldwide. The origins of Wireless Local Access Networks (WLAN) are the Local Area Networks, where, as the name states, computers were part of a local wired network on a fixed location, having access to shared resources, and incomparably higher amounts of information, data and applications (Dhanalakshmi and Sathiya, 2015).

The first version of WLAN, dating to the beginning of the decade of 1990, was unsuccessful due to the low speeds, high costs and impracticality of the solutions. By the end of the decade, some improved standardised technologies for WLAN started to take shape; however, IEEE presented what became the widely adopted standard, the IEEE 802.11. The very first versions of the standards were IEEE 802.11-1997 and IEEE 802.11-1999, the first describing the Medium Access Control and Physical Layer specifications for WLAN and the latter clarifying the standard. Due to the slow bit rates that made these standards unattractive, the version 802.11a and 802.11b were published in 1999 with higher speeds in the 5GHz and 2.4GHz bands respectively, becoming the first widely adopted WLAN standards (IEEE, 2019). Despite the numerous list of version, Wi-Fi

Table 2.2: Wi-Fi generations and subsequent specifications. Source: Abdelrahman et al. (2015)

802.11 protocol	**Release date**	**Frequency (GHz)**	**Band-width (MHz)**	**Base Data Rate (MB/s) Min-Max**	**Allowable MIMO streams**	**Modulation Antenna Technology**	**Approximate Rage (m)**	
							Indoors	**Outdoors**
802.11	Jun 1997	2.4	22	0.125 - 0.25	1	DSSS, FHSS	20	100
a	Sep 1999	5	20	0.75 - 6.75	1	OFDM, SISO	35	100
		3.7					-	5000
b	Sep 1999	2.4	22	0.125 - 1.375	1	DSSS SISO	35	140
g	Jun 2003	2.4	20	0.75-6.75	1	OFDM, DSSS, SISO	38	140
n **Wi-Fi 4**	Oct 2009	2.4/5	20	0.9 - 9.025	4	OFDM MIMO	70	250
			40	1.875 - 18.75			70	250
ac **Wi-Fi 5**	Dec 2013	5	20	0.9 - 12.04	8	OFDM MU-MIMO	35	-
			40	1.875 - 25			35	-
			80	4.06 - 54.16			35	-
			160	8.125 - 108.34			35	-
ax **Wi-Fi 6**	Sep 2019	2.4/5 1 - 6	20	1 - 17.02	8	OFDMA MU-MIMO MIMO	>35	-
			40	2 - 35.85			>35	-
			80	4.25 - 75			>35	-
			160	8.5 - 150			>35	-

is considered to have six Generations, seen in Table 2.2, that differ in operating principles while being backwards compatible.

Looking into more detail into the technical specifications of the six generations, similarities are identifiable between the different protocols. Dhanalakshmi and Sathiya (2015) provide a comparison between the first five generations, that complemented with the analysis by Bellalta (2015) for IEEE 802.11ax, build a good overview of their functioning. It is also to be underlined that IEEE 802.11ax, designated by Wi-Fi Alliance as Wi-Fi 6, was introduced only in September 2019 and is still being steadily adopted by the industry.

All generations, except for protocol b, use orthogonal frequency-division multiplexing (OFDM) as modulation scheme to encode data on multiple frequencies. In contrast, protocol b uses direct sequence spread spectrum as a modulation technique to employ a single input single output (SISO) technology. This is also the case for IEEE 802.11a and g, and only from Generation 4 was the technology able to support multiple simultaneous radio signals, in a Multiple Input Multiple Output (MIMO) fashion. This change also brought a dramatic increase in the range and throughput of Wireless networks. Wi-Fi 6 introduced a more efficient, improved, multi-user focused version of OFDM, orthogonal frequency-division multiple access (OFDMA). Together with MU-MIMO (multi-user, multiple input multiple output), Wi-Fi 6's throughput was sharply increased, and the power consumption significantly decreased.

Wi-Fi operates in the unlicensed spectrum, mainly at the frequency ranges of 2.4GHz and 5GHz, with some regional divergences. Using the example of the US, Wi-Fi at 2.4GHz band can operate without a Spectrum license since it falls under the Industrial, Scientific and Medical radio band with the risk os suffering interference with other technologies, such as Bluetooth devices and microwaves. Channels are 20MHz wide at 5GHz.

When it comes to the frequency band used, there is a subsequent trade-off between throughput and range. Due to the higher frequency rate, 5GHz bands are more susceptible to obstacles, such as walls, therefore having in general shorter ranges than 2.4GHz, but 5GHz is capable of higher throughputs. Wi-Fi 3 starts making use of multiple radio bandwidth, 20 and 40MHz, which makes the connection more susceptible to interference but enables higher throughput by using bandwidth more efficiently and merging channels. Wi-Fi 6 is by far the generation with the highest throughput, with maximum data rates in the order of 150 MB/s at 160MHz channels, while Wi-Fi 5 enables a maximum data stream of 108 MB/s, which surpasses the 18.75 MB/s maximum data spread provided by Wi-Fi 3 by over five times. When discussing data rates, it is essential to distinguish between throughput and goodput, where the first is the rate of total data transfer and the second refers to the useful data that is transferred over the network.

The range of the different generations is significantly linked to the frequency band, as mentioned above, and the antennas used. IEEE 802.11a offers a 5 kilometres outdoor range when operating at 3.7GHz. However, the indoor range values are more commonly around the 35 meters, and newer outdoor access points can range up to 150 meters. For the latest generations of Wi-Fi, there is no recorded outdoor range. It is possible to increase the outdoor range to many kilometres with the usage of directional antennas. Since Wi-Fi signal is susceptible to obstacles, the out-of-sight signal is degraded. To avoid interference at the same frequencies, these protocols use Carrier-sense multiple access with collision avoidance, so that access points can detect other devices using the same channel or any existing noise, and adjust accordingly by delaying transmissions. Wi-Fi 6 is least affected by interference.

As a layer of the security of WLAN networks, it is relevant to mention the various authentication methods, covered by IEEE 802.1X. Wi-Fi Protected Access (WPA) is the most widely used, using Pre Shared Keys (PSK). Extensible Authentication Protocol (EAP) is a WPA improved authentication and authorisation framework, that uses central authentication servers. The concept of Wireless Internet Service Provider roaming (WISPr), where the Universal Access Method must be used to provide access to the user in a fashion similar to cellular broadband networks, where users have to login in a captive portal to access the network (Marques et al., 2017).

Wi-Fi supports peer to peer communications through Wi-Fi direct, defined by Wi-Fi Alliance, based on direct device to device communications. Wi-Fi direct are networks where devices can behave both as an access point or clients, with the roles being negotiated seamlessly and logically assigned (Camps-Mur et al., 2013).

Most of the mobile devices such as computer and smartphones have their Wi-Fi interfaces built directly in the motherboards to avoid the additional separate network card. However, in vehicles, some OBUs have Wi-Fi antennas. To increase the range, these antennas are aimed to be placed outside of the car, avoiding the obstacles.

Today, Wi-Fi is the most commonly used wireless communication technology through which 60% of all the mobile data traffic flows, and it counts with 4,000,000 million devices shipped yearly and a cumulative number of 13,000,000 devices in use, according to Wi-Fi Alliance (2019). By November 2019, Wi-Fi presented a Global average download speed of 9.2 MB/s and an average upload speed of 5.05 MB/s compared to the 4 MB/s, and 1.5 MB/s obtained respectively by Cellular broadband technologies (Ookla, 2019).

The protocol IEEE 802.11ax is highly attractive for in-vehicle uses, as described by Akbilek et al. (2018) as a response to the demand to higher throughputs and to enable users the access to the network using their devices in-vehicle while offering lower-cost data pipes. Earlier protocols were proven by Bychkovsky et al. (2006) to be a feasible solution for Internet access in a vehicular environment. The widespread deployment of urban-scale hotspot networks represents a highly valuable infrastructure already installed capable of connecting not only user devices, but also vehicles. Lu et al. (2014) points out the challenges faced by the existing Wi-Fi standards, such as the different speeds at which the users are moving that decrease sharply the connection time by Wi-Fi Access Point, while the time spent in authentication, authorisation and IP configuration to establish the connection are very long for such short connections. Other challenges are the signal loss due to channel fading and shadowing, anomalies in radio propagation channels, and finally, the fact that these networks were designed for environments that do not include high mobility use cases. In the light of the 2014 technology, Lu et al. (2014) suggest as the improvements required for a sufficient Quality of Service Wi-Fi in vehicular environments the reduction of time for connection, the introduction of V2V multi-hop to increase ranges, improvements on the protocols for high mobility cases and further development of the infrastructure network of Wi-Fi hotspots.

2.3 Broadband Cellular Network Technologies

Broad Cellular Networks technologies refer to the mobile communications to which are carried on to the user wirelessly delivered through mobile phone towers to digital portable devices. These are usually divided into generations, and standardised by 3GPP, the entity developing and managing the standards for mobile telephony, from 2G standards such as GSM, GPRS and EDGE, to the latest 4G LTE and 5G standards. 3GPP's standards are based on releases, and it is common for these to be built on top of each other. The first generation was voice only based on analogue systems, and it dates back to the 1980s. 2G introduced the digital mobile systems that supported text messages in addition to voice communications and some limited data transmissions and 3G, first commercially launched in Japan in late 2001, brought the concept of broadband data systems enabling Internet access, video calling and other entertainment applications. The fourth generation, labelled Long Term Evolution (LTE) improved the internet access significantly by increasing the mobile broadband, and with this bringing Voice over Internet Protocols, streaming for both gaming and video applications, and others. With its first release deployed in 2009, by May 2019 LTE presented an 80% coverage across 87 countries Boyland (2019). 3GPP releases for 5G, designated 5G New Radio (NR) have already been published. However, this is still in the beginning phase of deployment, with South Korea taking the lead in October 2019 and by December first, Analysis Branch (2019) gathered that only nine companies with a total of 16 phone models were equipped to support 5G.

The International Telecommunication Union (ITU), a United Nations agency, is additionally a vital stakeholder in this sector as the organisation issuing the requirements for 4G and 5G networks, through the International Mobile Telecommunications-Advanced (IMT-Advanced) and IMT-2020 respectively. The process starts with studies around the desired services and technologies, market forecasts, and spectrum-related matters, such as needs and availability of frequencies. Evaluation criteria are set based on the conclusions of the studies, and the available technologies assessed according to those and the minimum requirements. The top six candidates are then evaluated in cooperation with other industry stakeholders. From there comes the standardisation phase, which is in charge of organisations including 3GPP and IEEE. These organisations first take the requirements, and proceed decide on the architecture and detailed specifications, that are posteriorly proven through testing and verification. This is an ongoing process, where processes are continually evolving.

For the purpose of this thesis, only LTE will be analysed as a current technology considered to connect cars. 5G will also be delved into as an option for future connectivity. It is important to underline that 3GPP has already included in their releases the concept of Cellular Vehicle to Everything (C-V2X), which aims to connect vehicles using 4G and 5G technologies. This is explored in section 2.5.

Araniti et al. (2013) analyse the usage of LTE for vehicular environments, motivated by the capacity for high data rates and low latency, with extensive coverage areas, and consider LTE a solution for the high bandwidth and Quality of Service (QoS) required for these environments for the various use cases related to infotainment. There is some limitation in the applications related to safety and traffic management since all communications using LTE necessarily go through the infrastructure, losing time and efficiency, and where V2V would be more appropriate. LTE is an all-IP based standard, giving it added extendibility and feasibility than previous generations, presenting latencies in the radio access up to 100ms. It also uses OFDMA for downlink connection and Single Carrier Frequency Division Multiple Access (SC-FDMA) for the uplink, and MIMO, similarly to Wi-Fi latest generations. LTE presents a wide coverage area that also functions for high node speeds and not being susceptible to low-density areas of vehicles or obstacles challenging the propagation of the signal. The market penetration is also highly favourable as widely used technology by most users. As for capacity, LTE offers up to 37.5 MB/s and 9.4 MB/s of downlink and uplink, respectively. There are some limitations as for the maximum number of vehicles per sell, and latency can be too high for critical safety applications.

Designed to connect societies seamlessly, 5G Networks go one step further to include cities, transportation systems, and user devices. IMT-2020 set the requirements for peak data rates in the orders of 2.5GB/s for downlink and 1.25 GB/s for uplink rates while the target for user experience data rates is 12.5 MB/s and 6.25 MB/s respectively. The use cases for connectivity while in movement should allow speeds of 500km/h and the designated bandwidth reserved to be at least 100MHz above the 6GHz frequency bands Wireless Broadband Alliance (2017). This makes of 5G the fastest generation, but also the one with the shortest reach, requiring more cells and, therefore, a higher infrastructural cost, resulting on higher prices per GB compared with the previous generations.

Boban et al. (2018) note that cellular technologies have not been designed to respond to low latency values and high-reliability requirements. 5G seems to have the most promising performance for these cases since 5G Automotive Association (5GAA) has been focusing on developing 5G V2X linked to the automotive industry to ensure the fulfilment of the use cases and requirements laid for vehicular environments. This is yet to be tested and verified at a full scale since 5G has recently just started its deployment.

2.4 Dedicated Short Range Communications

Toh (2001) defined the protocols and systems for ad hoc mobile wireless networks, or mobile ad hoc networks. There, he defined ad hoc wireless networks as "a collection of two or more devices equipped with wireless communications and networking capability", meaning that these devices can communicate among each other, either directly if within the radio range, or through intermediary nodes that relay the packet until it reaches the destination. The term ad-hoc stands for the capacity of the network to adapt and manage itself, where the nodes of the network detect each other, identify the type of device and its attributes, and proceed to perform the handshaking. In the subsection Car-to-Car mobile communication, Toh (2001) mentioned for the first time the concept of Car-to-Car mobile communications, that would be the foundation for Vehicular Ad hoc Networks, more commonly referred to as VANETs. In this use case, information is relayed among cars, having the infrastructure around the vehicles participate as nodes in the network and acting as gateways to the network. Additionally, he also described vehicle to vehicle (V2V) communications, where cars communicate with each other to transmit relevant information in the surroundings, with a focus on broadcasting safety-related messages.

The stakeholders around mobility and transportation have been making considerable investments in intelligent transportation systems as an endeavour to achieve smarter, safer, better informed, more coordinated and overall superior transportation networks. These efforts shape not only the in-vehicle technologies but also infrastructure and on-road technologies. The Dedicated Short Range Communications (DSRC) frequency channels result as a communication technology capable of fulfilling the requirements of extremely short latency for road communication.

Zeadally et al. (2012) defend that the first step in the creation of DSRC was the allocation of 75MHz of the spectrum at 5.9GHz by the United States Federal Communication Commission in 1999, which enabled the American Society for Testing and Materials to create DSRC as an adaptation of the IEEE 802.11a in 2003. Until very recently, in the USA, DSRC had exclusively reserved a free licensed spectrum, having seven channels with 10MHz with some reserved for specific purposes. This project was soon taken over by IEEE who addressed the limitations in their existing 802.11a standard group with the creation of Wireless Access in Vehicular Environments (WAVE). IEEE 802.11p addresses the lowest layers, working at the physical and data link layers of WAVE. The operational functions covered by the transport and network layers are handled by the IEEE 1609 standards, with IEEE 1609.1 focusing on the management activities, IEEE 1609.2 in security, IEEE 1609.3 defining the network protocol and IEEE 1609.4 supporting the upper media access control layer.

Regions present different standards, with slight differences in the radio frequency and channels. In Europe, CEN is designing the DSRC Standard, and it allocates 20MHz of bandwidth at 5.8GHz and possess four channels with 5MHz each, while Japan allocated 80MHz at 5.8GHz with seven separate channels of 5MHz each. Therefore, data transmission rates and coverage vary within geographies.

Within the European Union, ETSI (2019) recently submitted for the Vote phase of the ETSI Standards EN approval procedure the final draft of ETSI EN 302 663, a Standards for ITS-5G Access layer specification for Intelligent Transport Systems operating in the 5GHz Frequency band. The document predicts the regulations for the ITS-5G technology, and defines the physical layer and data link layer, based on the IEEE802.11p, under the label of C-ITS (Cooperative Intelligent Transport Systems). This translates in a yet to approve WAVE standard in Europe. Nevertheless, the European Comission (2019) recently regulated the usage of C-ITS on vehicles produced from early 2020.

In the USA, NHTSA released in late 2016 the mandate for V2V communications, taking over 17 years since the allocation of the broadband frequencies for that purpose. Further developments in the adoption of DSRC in North America seem to be ceased for the time being.

WAVE requires two types of devices: the Road Side Units (RSU) as the stationary device hosting the application providing services, and an On-Board Unit (OBU) on the vehicle and considered the mobile device which host peer applications using the services. These devices enable V2X communication, mainly by V2V and V2I communication skills. DSRC and WAVE can still function only with OBUs for a V2V communication (Zeadally et al., 2012).

With the insurgence of 4G and 5G based V2X communications - explored in section 2.5 - in 2017, the industry became divided over which one to invest in. Toyota (2019b) committed to FCC to install DSRC technologies in 2018 only to abandon such plans in April 2019, due to insufficient commitment from the remaining automotive manufacturers on adoption the technology, and underlining the instability and uncertainty around the 5.9GHz frequency band allocation as an additional reason. In August 2019, Toyota (2019a) further developed on this topic, defending the adoption of C-V2X in case this technology proves to be superior to DSRC. In December 2019, the FCC announced its intention of designating the lower 45MHz of the unlicensed band spectrums (Federal Communications Commision, 2019).

Some OEMs are already using this technology in small production volumes, such as General Motors, while others fully support C-V2X as is the case of Ford Motor Company (2019), that announced the deployment of C-V2X in all new US vehicle models beginning in 2022.

WAVE networks were designed and conceived with use cases primarily focused on security applications being, therefore, aiming towards the fast broadcasting of short, urgent messages. The limited scope of use cases, together with the high investment needed in infrastructure and RSU to enable WAVE brought limitations on the exploration of WAVE and DSRC as solutions for broader vehicle communications, together with the appearance of C-V2X solutions. The future of V2X communications is uncertain, without a clear direction for the future and which technology the automotive stakeholders will prefer.

2.5 Cellular Vehicle-to-Everything

In 2016, 3GPP (2016) (3rd Generation Partnership Project) announced the inclusion of a V2X standard in their Release 14, motivated by the ongoing initiative to expand LTE's applications and as a response to the growing data needs of the automotive industry. This standard predicts the usage of cellular for V2X communications (C-V2X), such as V2V, V2I and V2N. With release 15 from 2018 Q2, 3GPP broadened this definition to support the 5G based V2N use cases, and Release 16 expands the scope to include 5G direct communications for V2V and V2I (GSA, 2019).

In release 14, the device-to-device communications or proximity services from Release 12, together with a new communication interface, enable direct communications in a peer-to-peer manner, without the need to go through the LTE base station. Additional modes were specified to fulfil the needed reliability and latency levels. Mode 3 is responsible for scheduling and allocation resources while within coverage and mode 4 for out-of-coverage scenarios (Toghi et al., 2018).

C-V2X predicts the capacity for Device-to-Network (V2N) communications through the conventional cellular protocols, and the capacity for device-to-device to connected to the environments surrounding, such as the devices carried by pedestrians for V2P, considering the vehicles as devices for V2V communications, and devices embedded in infrastructures for V2I. Communications in C-V2X are carried out through the standardised 4G LTE and 5G cellular broadband technologies. The use-cases for the design of the solution are diverse and not exclusive to safety and traffic management scenarios, but technology enabling use cases for autonomous vehicles, new aftermarket and enhanced infotainment services and logistics applications (GSA, 2019).

This technology is still in the testing phase, in efforts encompassing the whole industry, from governments and policymakers to OEMs and tier-1 suppliers, and trials have been frequent in diverse locations, such as testing of on-road functionalities by the Victorian government, and Australian telco and Lexus in Australia, and city-wide C-V2X projects in Wuxi, China, involving the city government and China Mobile. Europe has been the stage to multiple trials and projects, and ETSI, the European Union, recognised organisation for the development, ratification and testing of standards for ICT systems.

In an analysis from September 2019, GSA (2019) identified the C-V2X ecosystem as having 25 active telecommunication operators from 16 countries spread across the globe participating in the tests and highlighted the availability of ready for market hardware, such as RSUs and OBUs.

The primary constraints for C-V2X are tied to the allocation of frequency band for C-V2X communications. There have been heated debates as a consequence of 5GAA's waiver request to the 5.9GHz band to allow C-V2X deployments, having yet to translate in a concrete decision, however, as mentioned in the previous section, Federal Communications Commision (2019) is since December 2019 considering to allocate the previously DSRC reserved frequency band to C-V2X.

Despite C-V2X's low maturity level, its potential has been shaking the market and dividing the stakeholders, a topic that is covered in the section above. As an additional side effect to the recency of C-V2X, there is substantial low coverage of this technology by independent entities that would be able to provide an unbiased analysis. Most studies around this topic are done by organisations supporting and developing the C-V2X technologies, such as 3GPP, 5GAA and NXP, and therefore, creating obstacles to the comparison of C-V2X to the possible alternatives.

2.6 Technology summary

In Table 2.3, the technologies covered in the earlier sections are summarised and compared in the relevant fields for this dissertation. It is possible to observe that Wi-Fi 6 and 5G present the most attractive bit rates and end-to-end latencies. The same applies for most of the remaining variables, with the exception of the mobility support and coverage, where cellular based technologies have a clear advantage. Another variable worthy of mentioning that is not conveyed in the table is that the technologies developed for mobility purposes are also expected to have a higher performance on V2V and other vehicular communication types. The prices of each are also not included, due to the uncertainty around the topic, however this is approached in Section 3.3. In general, there is some conjecture around the 5G and C-V2X, since these are experimental and predicted values, due to the low maturity level of the technologies.

Table 2.3: Comparison of the possible technologies to be used for vehicle connectivity. Source: Araniti et al. (2013)

Feature	**Wi-Fi 6**	**802.11p (DSRC)**	**LTE**	**LTE-A**	**5G**	**C-V2X**
Channel width	20 MHz - 160 MHz	10 MHz	1.4, 3, 5, 10, 15, 20 MHz	Up to 100 MHz	50 - 400 MHz	5 MHz (Uncertain)
Frequency bands	2.4 GHz, 5.2 GHz, 1-6GHz	5.8-5.9 GHz (Uncertain)	700 - 2690 MHz	450 MHz - 4.99 GHz	24 GHz - 72 GHz	5.9 GHz (Uncertain)
Bit rate	8-1201 Mb/s	3-27 Mb/s	Up to 300 Mb/s	Up to 1 Gb/s	Up to 2Gb/s	Up to 100 Mb/s GSMA (2018)
End-to-End Latency	0.12 ms	20 - 500 ms	>100ms Boyland (2019)	>100 ms	3 ms (uncertain) Al-Saadeh et al. (2018)	>15ms (uncertain) Emara et al. (2018)
Range	Up to 150 meters	Up to 1 km	Up to 30 km	Up to 30 km	Up to 1 km (expected)	Up to 1.5 km (expected)
Capacity	Medium	Medium	High	Very High	Very High	Very High
Coverage	Intermittent	Intermittent	Ubiquitous (dependent on geography)	Ubiquitous (dependent on geography)	Ubiquitous (dependent on geography)	Ubiquitous (dependent on geography)
Mobility support	Low	High (up to 250 km/h)	Very High (up to 350 km/h)	Very High (up to 350 km/h)	Very High (up to 350 km/h)	Very High (Up to 500 km/h relative speed)
V2I Support	Yes	Yes	Yes	Yes	Yes	Yes
V2V Support	Native (ad hoc)	Native (ad hoc)	No	Yes, through D2D	Yes, through D2D	Native (ad hoc)
Fully deployed and available	Yes	No	Yes	Yes	No	No
Market Penetration	High	Low	High	High	Potentially high	Potentially medium

Chapter 3

Problem Description

Since its origins, the automotive industry has continuously been changing and adapting to both the customer wants and needs, and to new technology developments, sometimes even taking up the lead in initiatives that affect not only the automotive market but the whole technologic landscape. It is only natural that in light of the growing connectivity trends across all sectors also influences the future of this industry. Several reports aggregate the future trends in four divisions: Connected, Autonomous, Shared and Electric Vehicles, usually referred to by the acronym CASE. Autonomous vehicles and Shared mobility represent the end motivation of the market, as it represents safer, more comfortable, convenient, efficient and environmentally friendly alternatives. Connectivity, hence, is the requirement to make it happen, and users are starting to perceive it as a commodity rather than a premium, with an increasing regulation requiring vehicles to be connected for safety reasons (Strategy& PwC, 2019), taking as an example the EU, where vehicles with the eCall functionality for emergency road assistance is compulsory since 2018. For this reason, users are less willing to pay for connectivity, making cost-efficient connectivity a vital requirement for OEMs.

The connectivity requirements associated with vehicles have peculiarities when compared to the other applications where the existing solutions were built around, such as smartphones and computers. These solutions have seen extensive investments both on scientific and regulatory efforts as well as in hardware and infrastructure. It is also essential to consider that data needs will sharply increase in the future. Hence, the cost of data should also be taken into consideration. Wi-Fi represents a widely available solution, with a low cost of data and extensive coverage worldwide, becoming a remarkably attractive response to the growing data needs.

As such, this chapter aims to analyse the market and the tendencies around connected vehicles, followed by an overview of the current applications and use cases behind the connectivity needs. A preliminary analysis of Wi-Fi as a solution applied in vehicles is made, as well as an explanation of how it could be adapted from the current applications to the vehicle-related environments.

3.1 Connected vehicles

The booming of technology and connectivity is changing and influencing from manufacturing processes and supply chain to customers' demands and expectations. The automotive industry, together with many others, evolved from a global supply-driven world into a demand- and influencer-driven detached segments. Seamless integration with the ecosystems is a requirement, and automotive is experiencing new mobility and business models. It comes as no surprise that connectivity and digitalisation have been ranking as the most significant automotive key trends up until at least 2030 according to the yearly KPMG International (2019) Automotive Report.

When analysing the shifts in the automotive industry, several forces come into play. Technology acts as a push agent and an enabler of connected, electric and autonomous vehicles, while customers expect an on-demand, multi-modal, shared mobility. Governments are pushing changes with regulations, taxes and subsidies, data-related regulations, sustainability policies and infrastructure management.

In Figure 3.1 an evolution of the vehicle parc (all registered vehicles in operation within a location) is shown from 2018 to 2030, including the growth on the number of autonomous, electric and connected vehicles. There is a clear trend, where in the future almost all the totality of cars will be equipped with internet access and having a wireless local area network. Strategy& PwC (2019) state that connected services, based on new digital vehicle service types such as features as a service, connected services and fifth screen connected services, will grow to be $81,000 million only in the USA, EU and China by 2030. In the report, Strategy& PwC (2019) also state that the profits for the OEMs will face diversified challenges, heavily depending on the pricing strategy and cost-efficiency of data usage.

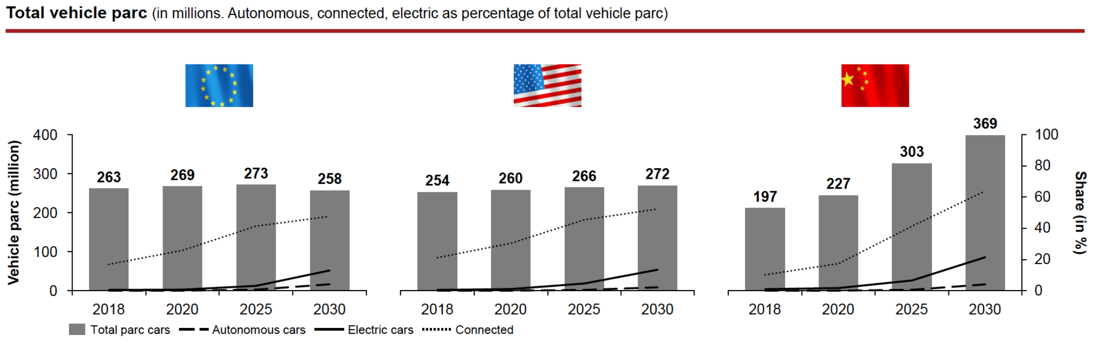


Figure 3.1: Total vehicle parc (in millions) and autonomous, electric and connected cars (in % of the total vehicle parc). Source: Strategy& PwC (2019)

Vehicles are becoming an increasingly complex system, with over 100 different electronic control units powered by more than 100 million lines of code (Embitel, 2018). These numbers are exponentially growing due to connectivity and electrification of mobility, where most functions are controlled by software. This industry is, therefore, now witnessing a disruptive digital transformation, where the differentiation and success are ever more depending on how well the stakeholders can use software to their advantage.

Connectivity takes the enabler role for future trends, and it becomes a prioritised requirement within the automotive world. The very first connected car was launched in 1996 by General Motors, with limited availability in high-end models, and connectivity has dramatically improved from availability to capacity, and users depend on connectivity more than ever for most of the day to day tasks. Connected vehicle solutions aim to bring economic growth and decrease the environmental impact of mobility by tackling traffic issues, improve safety through driving assistance systems and more autonomous vehicles, and improve the Quality of Experience of drivers and passengers through a ubiquitous and seamless in-vehicle connectivity.

Connected vehicles consist of any vehicle equipped with that hardware needed to enable wireless communications with the internal and external environments. Collectively, these vehicles compose a dynamic mobile network where information is collected, processed, shared computed and secured and provide the foundations for the creation of intelligent transportation systems.

Currently, there are about 49.5 million connected cars, with a historical year on year growth of 33.7%. The first and probably most crucial dimension due to the necessity of connectivity to enable the remaining ones consists of the capacity for vehicles to network with the outside world. This has two high-level concepts, one being focused on the car, where the vehicle is capable of connecting to other vehicles, the infrastructure around it, the cloud and the internet. The second dimension is the passengers' connectivity, which implies a seamless connected experience to the outside world while on the move. 34% of the European consumers already expect seamless connectivity with their vehicles and other car services, while in China, this share is 89%. It is no surprise that the percentage of total cars on the roads in 2030 will be higher than 60% worldwide (Strategy& PwC, 2019).

Connectivity poses a very seducing capability for OEMs since it enables new profit streams and yield per vehicle even after the vehicle is sold. Some new digital-based services will be vehicle features as a service that can be activated over the air and paid per use - like additional battery reach -, and subscribable or bought vehicle connected services that allow the user to manage the vehicle better or to access the digital world through the car, or merely support driving functions.

Another window of opportunity comes from access to third-party services or products through the vehicle's systems that users can buy or subscribe to while OEMs receive a commission. Connectivity makes data gathered on the vehicle and user easily accessible, bringing not only valuable insights that can be capitalised direct by being sold or by being used in research and development (Viereckl et al., 2018).

The totality of the new cars produced and sold are expected to be connected by 2022, and 6 out of 10 users make their purchase decisions based on car connected capabilities, making it vital for OEMs to focus on this topic.

Furthermore, the increasing vehicle's reliance on software and dependency on data brings critically to the capacity to update or correct the vehicle software continuously over the air (OTA). On its turn, this ability makes cars upgradable opening the doors to new business models and additional revenue streams.

Connectivity in moving vehicles poses additional challenges when compared to static situations, due to a large number of vehicles receiving and sharing information at high speeds in complex geographical environments. These vital changes in use cases require an off-the-shelf, new technologies dedicated to this purpose.

3.1.1 Autonomous vehicles

SAE International (2018) issued in 2014 the first edition of "Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems", and since then it has been the most cited reference for Automated Vehicle Capabilities. According to this standard, there are six levels of automation, from level 0 (no automation) to level 5 (full vehicle autonomy). Figure 3.2 has a more detailed view over the six automation levels, such as what the driver is expected to do at each level, what are the driving and support features as well as examples. The driver is expected to perform all or most of the dynamic driving tasks from level 0 to 2. From level 3 on, automated driving systems take over and perform the entire dynamic driving tasks while engaged.

Level 1, designated as driver assistance features, consists mainly of computer assistance of simple functions. These features have been available since the late 20th century with the introduction of ABS and cruise control.

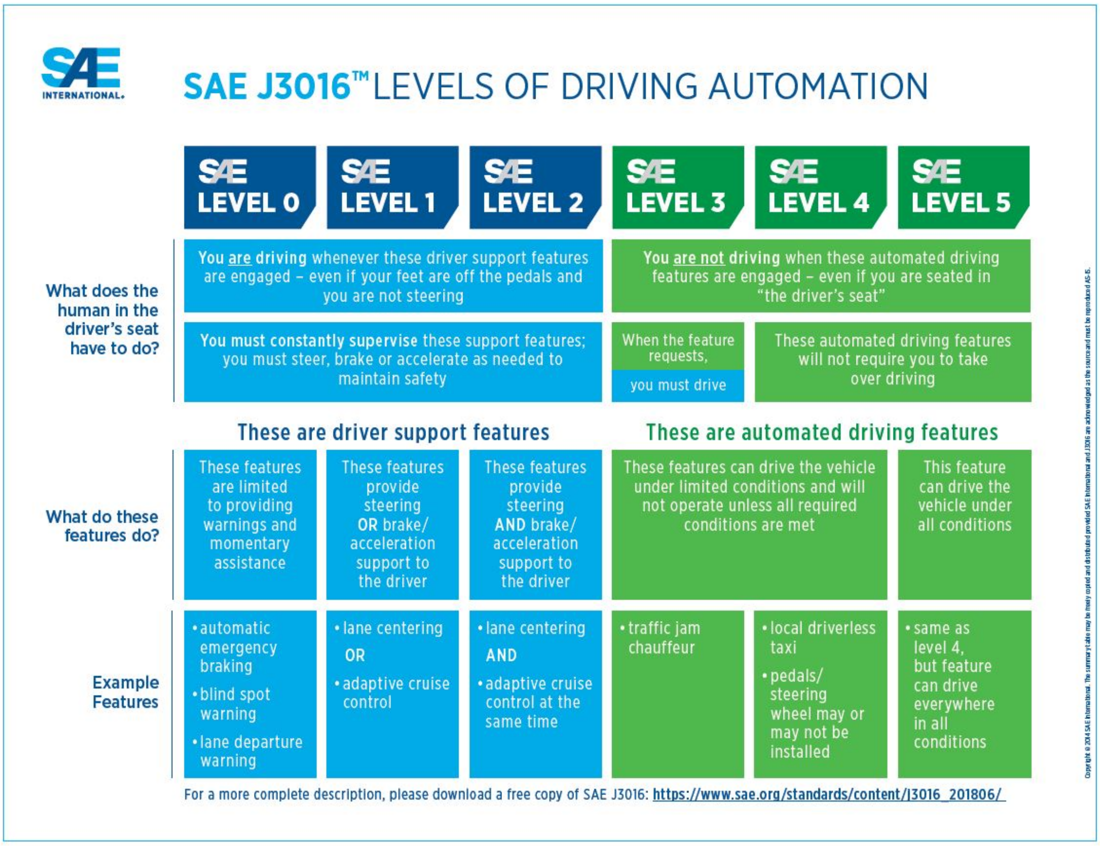
Partial driving automation, level 2, is characterised by the system taking over the vehicle motion control. Automatic emergency braking, introduced in the market around 2000, is an example of the features defining this level. The ability to make tactical decisions while engaged and detect as well as respond to objects and unexpected events marks the threshold for the system having a more active role than the driver.

In level 3 vehicles, the driver is no longer required to control the vehicle for some operational tasks nor to react and respond to objects or events in some domains.

The distinction between Level 4 and Level 5 lies on the domains where the system performs, where level 5 has a sustained and unconditional role over the driving tasks, and there is no request or reaction needed from the driver. The driver becomes a passenger. Level 4 has the same degree of independence applied only to limited domains.

Despite the current fast-evolving technologic ecosystem, the highest level of automation in the market is level 3, enabling conditional driving automation under certain conditions. The currently most common and known examples of autonomous driving systems are Cadillac’s Super Cruise and Tesla’s Autopilot that enable lane keeping, lane changing, distance keeping and cruise control. These are merely between level 2 and 3 of automation.

Nonetheless, autonomous vehicles are still somewhat limited by legal frameworks, guidelines and regulations around the topic. USA assumes the role of accelerator worldwide to the development of AVs. This position comes as a result of more flexible legislations that allow testing and usage of AVs in some circumstances. Over 80% of the vehicles currently on the road are still at level 0 autonomy (Walch, 2019) in the USA. However, around 80% of the new vehicles sold in 2018 were at least level 1, with level 2 taking over most of the sales by 2025.



SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			**These are automated driving features**		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/acceleration support to the driver	These features provide steering AND brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering OR • adaptive cruise control	• lane centering AND • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

For a more complete description, please download a free copy of SAE J3016: https://www.sae.org/standards/content/J3016_201806/

Figure 3.2: Levels of driving automation and associated features. Source: Shuttleworth (2019)

One of the critical factors for the development of these systems is data and connectivity, not only to the network but to the environment surrounding them. In order to successfully develop and produce reliable vehicles capable of real-time decision making, there is a need to both collect, process and transfer data and to train its AI systems. Hence, further developments on vehicle connectivity are needed to sustain advancements on more autonomous vehicles.

3.1.2 Shared vehicles

Sperling (2018) describes shared mobility powered by electrification and automation as the key to reducing urban congestion and emissions. This belief is based on the economic advantages of shared mobility and new ways to enable shared mobility created by technologies such as smartphones, wearables, real-time location-based services and connectivity. Sperling (2018) also points out that a study carried in New York showed that three thousand four-passenger vehicles, corresponding to around 20% of the current Taxi vehicles in New York City, would be enough to serve 98% of the Taxi demand while having only less than 3 minutes of waiting time.

Shared mobility is far from being a new phenomenon in the mobility world. The first car-sharing program was created in 1948 in Zurich, Switzerland. Several others followed, not only around cars but also bicycles, lasting only for a few years before dying. The end of the century brought the sustainable shared mobility business models powered by the developments in location technology and connectivity (Shaheen et al., 1998).

Another factor supporting the growth of shared mobility comes from the behaviour shift in large cities: combustion engines will be banned, congestions and regulations limiting private vehicle's access to the inner areas. On the whole, it will be imperative for OEMs to retain their role as highly productive designers of high-quality vehicles and to broaden their scope to provide the users with enhanced digital services. Within shared mobility, there are two prevalent concepts: car-sharing and ride-hailing, wherein the first users are still driving the vehicles that they choose from a specific station or free-floating either from fleet providers or private ownership, and in the second where users do not drive, and mobility is provided as a service - MaaS. In 2017, ride hauling had already 338 million users.

Recently Viereckl et al. (2018) have pointed that the 2017 market for shared on-demand vehicles is worth around $87,000 million, growing to $1-4 billion by 2023 in the USA, EU and China alone. Fomented by the increasing connectivity in new cars, heading to 100% by 2022, this business model, described as mobility as a Service (MaaS), will in 10 years account for 22% of the automotive revenue, compensating for the declining individual sales. As a result, it is essential to make the shared mobility experiences still personal, seamless, multi-modal and on-demand.

3.2 Vehicle connectivity needs

To evaluate Wi-Fi as a solution for connectivity, it becomes essential to define the applications and the concrete data needs by vehicles. This exercise proved to be challenging since currently, connectivity is particular from OEM to OEM and the future market predictions do not converge to a certain point. For this purpose, the direct input from different OEMs and some information used by the entities designing the C-V2X such as 5GAA, and 3GPP is used. Applications were categorised in two distinct groups. Boban et al. (2018) describes applications where short, high data-rate connections suffice to fulfil the delay-tolerant exchanges, such as map updates or non-urgent software updates, exchange non-real time infotainment in the downlink, and car and driver-related data as well as traffic data in the uplink. The applications with such characteristics were referred to as delay tolerant. The other group consists of the applications needing constant data exchange in real-time, with exceptionally low latency levels, being the case of safety functions and streaming services, from hereafter referred to as delay intolerant applications. These are differentiated through the delay tolerance.

To define each application, the following variables are considered: minimum and maximum data size (when applicable), data rates for download and upload (when applicable), maximum delay and frequency, together with the corresponding sources. Some of the information was provided from specific industry stakeholders, and consequently, for confidentiality purposes, their names shall remain anonymous and referred to as OEM 1, OEM 2, Map Provider and Tier-1 Supplier. These applications can be found in Table 3.1 and Table 3.2, divided respectively by delay tolerance and non-delay tolerance. The first has the added field of frequency since these are based

Table 3.1: Delay tolerant application definitions and corresponding data related needs.

Applications	**Minimum size**	**Maximum size**	**Maximum delay**	**Frequency**	**Source**
Software update (Critical)	50 MB	5,000 MB	1 day	Yearly	OEM 1
Software update (Non critical)	1 MB	32,000 MB	7-14 days	Monthly	OEM 1
Firmware update	50 MB	5,000 MB	10-14 days	Semesterly	Tesla
Basic map update	1,000 MB		3 days	Weekly	Map Provider
3D City model update	10,000 MB	20,000 MB	10-14 days	Quarterly	OEM 2
Dynamic map updates	0.001 MB	1 MB	36 minutes	Twice a day	OEM 2
Unit configuration update	20 MB		10-14 days	Semesterly	OEM 2
Machine learning model update	1,000 MB		10-14 days	Semesterly	OEM 2
Usage based insurance	0.5 MB	10 MB	10-14 days	Daily	Tier-1 Supplier
Predictive maintenance	0.015 MB	0.5 MB	10-14 days	Daily	Sample File
ECU update embedded	1,000 MB		10-14 days	Monthly	OEM 2
Swarm functions	0.3 MB		-	Daily	Veniam

on data packages to be sent or received in certain frequencies rather than continuously. This is not the case for the latter, where data traffic capable of supporting the constant data exchange with minimal latency values is expected.

As covered in the previous sections, the connectivity needs from vehicles are going to increase drastically, especially when considering autonomous vehicles, that create and process a massive amount of data to support the driving task, directly proportional to the number of sensors, data resolution and devices associated. The AVs currently used test generate, on average, 5 TB, going up to 10 TB compared to the daily 650 MB by users on their personal devices (Accenture, 2018).

Some of the applications covered are not yet commercially deployed, taking as an example the features related to autonomous driving and the infotainment features, including VR online gaming in vehicles, online gaming since such features require higher levels of vehicle automation to ensure the drivers and passengers safety.

Table 3.2: Delay intolerant application definitions and corresponding data related needs.

Applications	**Data Rate Download**	**Data Rate Upload**	**Allowed Latency**	**Source**
Music streaming	70 MB/h	-	3 sec - 5 min	Techbook (2018)
Video streaming	140 - 1,500 MB/h	-	3 sec - 5 min	Techbook (2018)
Remote car control trajectory	15 MB/s	0.5 MB/s	100 ms	Tier-1 Supplier
Live remote car control	15 MB/s	0.5 MB/s	40 ms	Tier-1 Supplier
Online Gaming	3 MB/s	0.5 MB/s	150 ms	Dilley (2019)
VR online gaming	400 MB/s	400 MB/s	20 ms	Mangiante et al. (2017)
Cooperative awareness	5–96 kb/s	5–96 kb/s	100 ms	Boban et al. (2018)
Cooperative sensing	5–25,000 kb/s	5–25,000 kb/s	3 ms	Boban et al. (2018)
Cooperative manoeuvres	10–5,000 kb/s	10–5,000 kb/s	100 ms	Boban et al. (2018)
Vulnerable road user (VRU)	5-10 kb/s	5-10 kb/s	100 ms	Boban et al. (2018)
Traffic efficiency	10–2,000 kb/s	10–2,000 kb/s	>1s	Boban et al. (2018)
Tele-operated driving	>25,000 kb/s	>25,000 kb/s	5 ms	Boban et al. (2018)

3.3 Price Comparison of the available technologies

In 2019, Cable.co.uk (2019), for the first time, collected information on 6313 SIM-only data plans from 230 countries and analysed in order to provide a comparison and analysis on the cost of 1GB in different countries. The result was an overview of the number of plans from each country, the minimum, maximum and average price of GB, and a global summary of these. On the report, Asian countries provide a median average cost per GB of $2.25, ranking as the second cheapest, with 10 out of the top 20 positions being occupied by these countries while having the most developed nations at the other end of the table. The telecommunication technology leader South Korea ranks as the most expensive Asian country with an average price of $15.12, and larger economies, such as China and Japan, presenting some of the highest prices per GB, while India presents the cheapest average cost of Data with $0.26/GB. Contrarily, North America and Oceania rank as the most expensive regions, with median prices per GB around $12 and $11.5 respectively. Western Europe presents a wide range of prices, starting from Finland with $1.16/GB and Denmark with $1.36/GB and going over $18.5/GB for Malta and Switzerland. However, the median price of the region is around $6.42/GB. In a global note, the median average price of cellular data per GB is about $5.26. More information on this study can be found in Appendix A.

When approaching the question of the price of Wi-Fi, the question becomes somewhat more intricate. One option would be to investigate the private broadband and Wi-Fi packages and prices, while other options would go across the usage of Wi-Fi aggregators with flat fees or credentials for public hotspots. If analysing the prices of broadband internet, where these are most commonly not calculated per GB but rather by month, since in most countries the offered packages include unlimited broadband. According to Cable.co.uk (2018), and a study conducted between August and October 2018 examining 3303 packages in 195 countries demonstrated a median global monthly price for broadband internet of $58.22, however, the usage allowances in this study are not presented, making of it a limitation. More information on this study can be found in Appendix B. If considering the price of Wi-Fi aggregators where a yearly flat rate can be acquired for the value of $30.00 yearly per device, or the price of global Wi-Fi providers such as FON, where a subscription for their worldwide network of hotspots can be obtained from the users' local provider portal. Taking as example a FON license acquired by NOS in Portugal, the prices range around €24.90 per month. The more significant urban centres and cities also have open free Wi-Fi networks that can be used for no fee.

It is essential to underline that the study in question is focused on end-user private plans and internet packages and that companies and OEMs have access to other cheaper offers based on economies of scale. The difference in pricing models and strategies for Wi-Fi and mobile data prices make it hard to compare both technologies.

For the C-V2X and DSRC technologies, it is not possible to price, since they are yet to be fully operational and launched, and the infrastructure also not planned.

3.4 Wi-Fi Availability

Strategy& PwC (2019) has reported that some of the major challenges are linked to the availability of the infrastructure - mostly for V2I communications, limited coverage of high-speed cellular broadband technologies and the necessity for cost-efficient solutions. This is a logical conclusion, when observing the investments required to build a C-V2X or DSRC network, or when using cellular broadband technologies, that were not designed for this purpose. Wi-Fi represents a solution that optimises the already existing and installed infrastructure that is currently heavily under-utilised.

Wi-Fi hotspots represent the most compelling connection points to vehicles since these networks are public, and wherewith the same credential it is possible to connect to diversified Access Points in different geographies. The introduction of Aggregators such as iPass, or Worldwide Wi-Fi providers, that include Boingo and Fon, that have an extensive portfolio of Public Wi-Fi networks worldwide. There are two relevant types of hotspots: the hotspots installed by the operators for that dedicated purpose, and homespots, where the routers installed to end customers broadcast two different SSIDs, the private one, and a public one (Tefficient AB, 2016). In 2018, there were 340.9 Million Wi-Fi hotspots, of which 12.2 million were commercially managed, and 328.6 million are homespots (Katz and Callorda, 2018). According to Fellah and Gabriel (2019) from WBA (Wireless Broadband Alliance), there will be 542 million hotspots by 2021. Currently, most of these hotspots are extremely under-utilised, except for hotspots located in airports and other high concentration tourist areas.

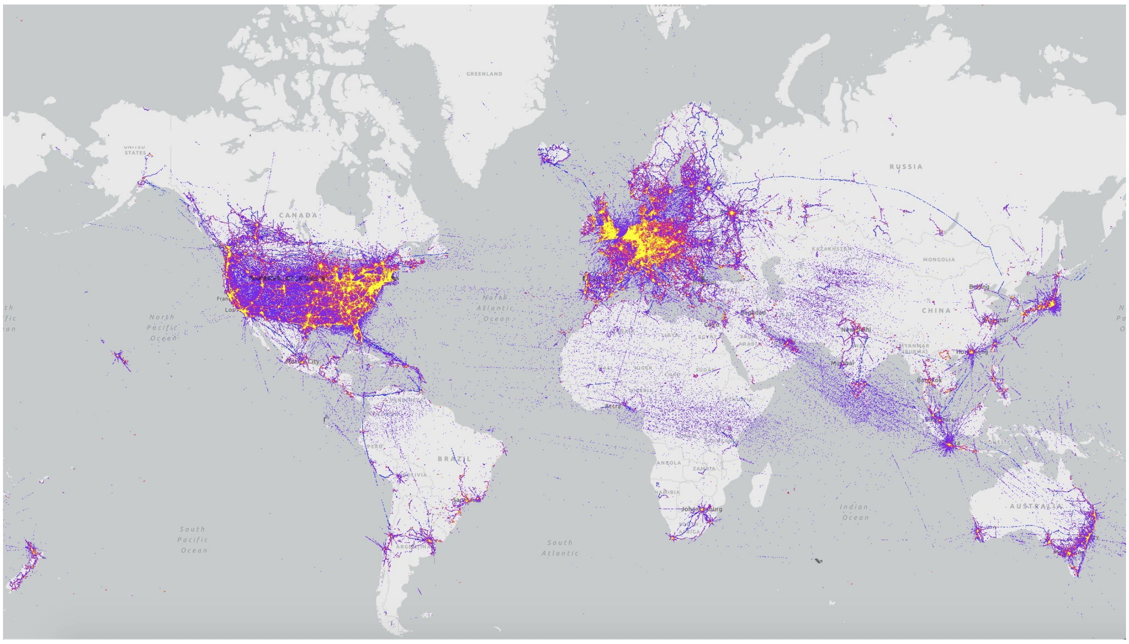


Figure 3.3: Heat Map with density of Wi-Fi SSIDs worldwide. Source: WiGLE (2019)

WiGLE (2019), where WiGLE stands for Wireless Geographic Logging Engine, offers a real-time overview of all detectable networks worldwide. In Figure 3.3, it is possible to see the density of Wi-Fi networks, measured through the different SSIDs, worldwide. In December 2019, WiGLE had reported 601.6 Million unique Wi-Fi networks globally with an associated GPS location. It is possible to observe that more developed countries in Europe and North America, as well as in the Pacific area, present a higher density of Wi-Fi networks. As for the encryption of these networks, WPA2 protected networks are the most common, with 66.5% of the total number of networks. 3.58% of the Wi-Fi networks are not encrypted, corresponding to 21.8 million networks, and 19.2% have unknown encryption, that includes the EAP protected networks. When analysing the growth of the total number of networks through time, there is an identifiable growing trend, seen in Figure 3.4, as well as in the number of new networks installed. The average number in the past years seems to be stabilising around the 250,000 new Wi-Fi networks daily.

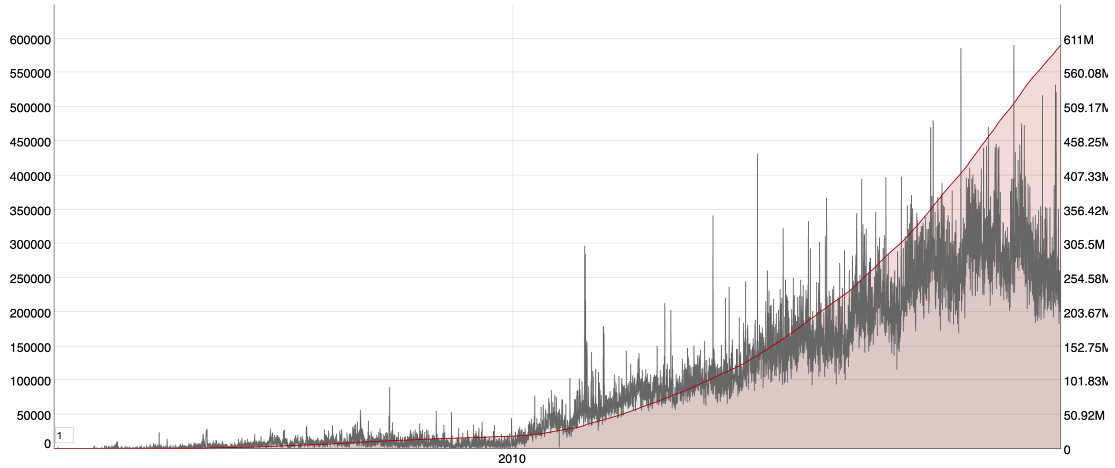


Figure 3.4: Evolution of the number of available Wi-Fi Networks over time. The grey line represents the number of new networks per year, and the red area the cumulative number of Wi-Fi Networks. Source: WiGLE (2019)

3.5 Connecting vehicles using Wi-Fi

For vehicles to efficiently use Wi-Fi networks, the company had to create its own solution and architecture to enable connections without a user interface and establish them as fast as possible to take advantage of all the possible connections while on the move. In order to decrease the time for connection, Veniam's product has two agents that work together to make autonomous decisions. In the standard individual user equipment, such as phones and computers, the first stage of establishing a connection is a network scan for all the available SSIDs. This scan usually takes 5 to 10 seconds, and after search all the channels along with the bandwidth, it returns the available connections. The company's product optimises the scanning process to ensure that connections are established as soon as possible.

Another difference from the standard architectures is linked to the connection drop and handover. On regular user devices, in order to ensure that ongoing downloads and applications are not dropped every time, there is a connection change, connections are kept for some seconds after the signal is lost, to build seamless handovers. When taking in consideration the in-vehicle scenarios, where it is vital to profit on all the possible connection times, once the signal is lost, the connection is dropped without waiting for a necessarily better Wi-Fi network and switching to cellular networks. Veniam also supports seamless handovers between technologies and different networks when using IP mobility, a protocol enabling a change of the connection network used without any modification of the device's IP, translating in undisrupted connected activities when the device changes the connection. To optimise the solution and make the solution scalable to millions of vehicles, Veniam reuses previously assigned IPs whenever connecting to a new network, saving hundreds of milliseconds in the connection process.

With its latest release, the Veniam's platform supports a handover between cellular technologies and Wi-Fi of 200ms (check), and the handover time between different Wi-Fi networks is dependent on the number of Wi-Fi antennas on the vehicle. With two or more radios, the vehicle can establish fast connections, since it can start the handover process while being still connected to the first Wi-Fi network. Veniam's product is capable of connecting to open networks, with no authentication required, open WISPr networks and WPA2 protected networks using PSK, EAP-TLS and EAP-TTLS authentications methods. When there is a connection established, the platform manages the applications' request for connectivity according to the needs and priorities.

These operations are compatible with any Wi-Fi generation since the hardware manufacturers are responsible for updating the chipsets accordingly.

Chapter 4

Methodology

This chapter describes the methodology behind the product analysis. For this, the information presented in Chapters 2 and 3 is translated into an examination and testing of the product in terms of results, costs, and availability, followed by a comparison to the required performance by the market and the available alternatives.

As the first task to evaluate the product, two tests were designed and performed in the company's testbed. A description of the testbed is presented first, followed by the two tests, the first being for delay-tolerant application, and the second for delay intolerant applications and testing of the traffic capacity of the product. For this purpose, the use cases explored in Section 3.2 were used to create the use cases and evaluate the solution, divided accordingly as delay tolerant and delay intolerant applications.

4.1 Test environment

The company's testbed consists of five OBU places inside different STCP buses running daily in the city of Porto. The buses route changes daily, however, most of the weekdays they drive for around 100km and 8 hours, where the driving intervals range from 06:00 to 23:00. During the weekends, these times, distances and intervals are shorter, and it is possible that the buses are not used at all. In Figure 4.1, an example of a full day bus route is displayed. In pink, it is possible to observe the part of the route taken by the bus without Wi-Fi connectivity, while the Wi-Fi connected routes are displayed in green. It is also possible to see that the bus was assigned to take that same route several times throughout the day since different traces are visible in the same streets. It is also observable the higher density of successful connectivity opportunities in the centre of the city.

Since the units composing the testbed belong to a commercial fleet, the driving behaviour is distinct from a private vehicle. Some of the differences consist of the number of stops, that inherently influences the average speed of the vehicle and driving times. It is still possible to normalise the results to average private vehicle driving times, and making inferences to approximate the results as much as possible to private-use vehicles.

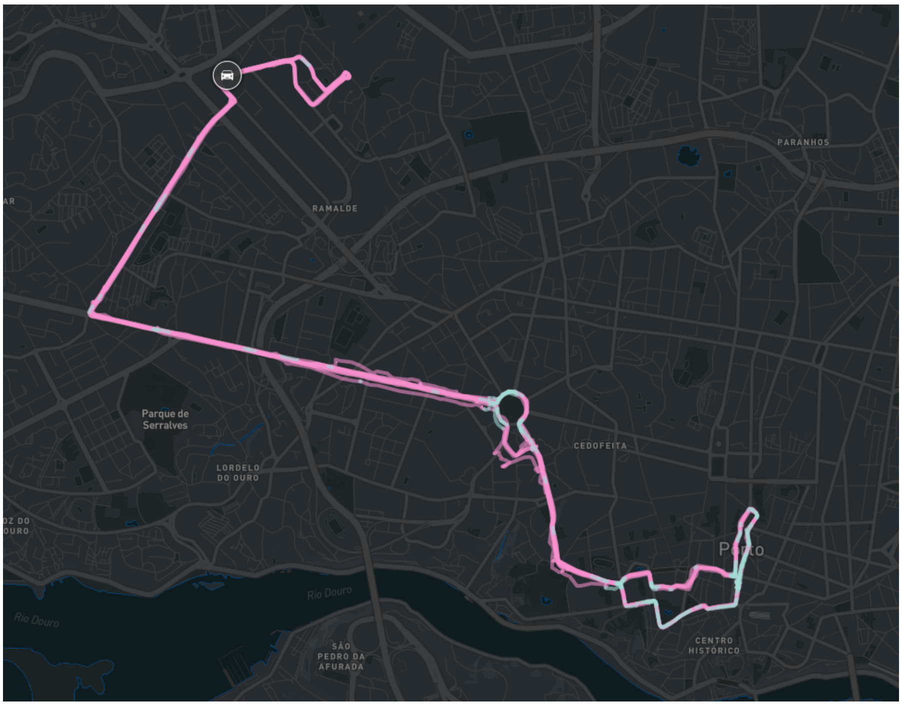


Figure 4.1: One of the bus routes visualised in Veniam's NOC.

The vehicles were configured to connect to different types of networks and providers, with different authentication methods and security protocols. Table 4.1 presents the four mentioned networks, where the first one consists of six Wi-Fi access points spread across the city and managed by Veniam. The second consists of the open network provided by the city of Porto with 120 outdoor hotspots and 190 access points covering mainly public areas and the city centre. The last two networks are constituted by hotspots belonging to two leading Portuguese telecommunication companies: MEO and NOS. These networks have thousands of homespots with the SSID of MEO-WiFi and NOS_WIFI_Fon. These last hotspots from MEO and NOS have a speed limit of 2 MB/s for both download and upload speeds.

4.2 Delay-tolerant use cases test

Considering as delay-tolerant applications those that have an allowed latency over one minute, the use cases displayed in the Table 3.1 were used to create applications to be sent and received

Table 4.1: Networks configured in the testbed vehicles used for the tests.

Wi-Fi SSID	**Authentication Method**
veniam_test	WPA-PSK
WiFi Porto Digital	Open network with Captive Portal
NOS_WIFI_Fon	Open WISPr
MEO-WiFi	Open WISPr

Table 4.2: Delay tolerant applications used for the test.

Application description	**File Transfer Direction**	**File Size**	**Priority**	**Delay Tolerance**	**Frequency**
Urgent Software update	C2V	3000 MB	High	3 hours	Once a year
Software Update	C2V	3000 MB	Medium	7 days	Every Month
Basic map update	C2V	1000 MB	Low	7 days	Once a month
Unit configuration update	C2V	20 MB	Low	7 days	Every Week
Dynamic map updates	C2V	1 MB	High	36 minutes	Twice a day
Usage based insurance	V2C	5 MB	Medium	7 days	Every day
Predictive maintenance	V2C	0.5 MB	Medium	7 days	Every day

on the testbed using the Veniam's platform. These render into the applications described in Table 4.2. The first two applications consist of software updates, where Urgent Software Update are imperative updates to fix a critical bug or malfunctioning of the vehicle that might pose a threat to the passengers' safety, being, therefore, less delay-tolerant and having a higher priority in the transfer queue. The second one is associated with a regular, periodic software update with either minor bug fixing or software upgrades, and, therefore, has a medium priority in the queue, and a higher delay tolerance and frequency. The basic map update application refers to the update of the maps sent by map providers. Due to the non-criticality of this application, priority was defined as low, with a high delay tolerance and a monthly frequency. Unit configuration update refers to updates of ECU or single specific components of the vehicle. Dynamic map updates concern road and traffic conditions, such as construction works or other abnormal, temporary situations that might interfere with traffic and be relevant for the user. Since these are updated more than once a day, they have a high priority and lower delay tolerance, since otherwise, data might become obsolete. The last two applications are sent from the vehicle to the cloud, and they refer to the data needed for usage-based insurance and predictive maintenance services. These have a medium priority and higher delay tolerance, since the need for real-time data is low, and they are to be sent in daily packages. In order to replicate these files, seven different files were generated to match the required sizes, since the content of the packages does not affect or impact the results.

The Veniam platform allows the setting of diversified policies to ensure that the transfer of packages is done according to the requirements. In order to fulfil the desired prerequisites of the applications described above, five policies are described in Table 4.3 matching each of the combinations required to send and receive the files in the desired fashion. Delay-tolerance represents the validity of the file to be sent over Wi-Fi after which the file is either discarded or sent by other available technologies, which in this case is limited to cellular broadband technologies. Priorities are used for the file queues, in case there are two or more files to be transferred. Higher priority files are sent or received first, and lower priority files are moved down the list.

The test duration was of a full week, seven days, from Wednesday to Tuesday, to ensure that all the applications could be tested under different conditions. To guarantee a representative test with well-distributed files transfers, the scheduling of the transfers was done in advance, with random time allocations within 09:00 and 20:00. In each vehicle during the test period, the first four files

Table 4.3: Transfer policies defined.

Name	**Priority**	**Delay Tolerance**
Urgent Software Policy	High	3 hours
Urgent maps updates	High	36 minutes
Medium Delay Tolerant applications	Medium	168 hours
Low Delay Tolerant applications	Low	168 hours

were sent once, also decided randomly, while the last two files were sent daily at random times and the dynamic map updates were sent twice a day.

The test was conducted through Veniam's NOC (Network Operations Centre), the user interface developed by the company, and using in-vehicle dashboards to monitor each vehicle and upload files to the cloud. Through these two User interfaces, files could be uploaded or downloaded to the vehicle, while using the appropriate policies. Due to the considerable size of the first three files, a short script was written to divide the files into smaller pieces of 100MB and submit them with the fitting policy. Taking as an example the Urgent Software update, the script generated 30 random files, submitting them to Veniam's NOC directly through the cloud by generating 30 transfers with the policy Urgent Software Policy. This eliminated the need to upload a 3GB file to the cloud whenever creating a transfer on NOC, a process that proved to be lengthy and unreliable, since the version of the software used, despite being the latest, is a prototype of the final product to be delivered to customers.

To analyse the results, Veniam provides with its product a data functionality with its product that enables an overview of the connection events, traffic volumes, downloads and uploads performed at the vehicles and each OBU. For the performed tests, data was extracted from Veniam's cloud and then proceeded to be treated. For the first test, data relating to the transfer events was obtained, providing for each event the timestamp for the submission of each file, the device IDs, time to start the download, total download time, downloaded size, number of attempts for a successful transfer, among other features.

In total, to the five vehicles available for the test, 32 files were transferred over seven days, where 18 were downloaded to the vehicles and the remainder 14 uploaded. For each of the use cases, the expected reliability from a Wi-Fi-based solution is calculated using the success rate, further described in the Section 5.1.

4.3 Delay intolerant use cases test

A second test was performed to evaluate the platform's performance in delay intolerant use cases. For this purpose, the availability of Wi-Fi and the throughput for each connection were measured to be compared with the requirements exposed in Table 3.2. Each vehicle's OBU was installed with *iperf*, a network performance evaluation tool, generating TCP data streams in the upload direction for two of the available vehicles and downloading in the remaining two. The

Table 4.4: National average driving times per week by country. Sources: Pasaoglu et al. (2012), US Department of Transportation (2017), Numbeo (2020)

Country	Average driving weekly time
Portugal	6.5 hours
Spain	10.5 hours
United Kingdom	8 hours
Germany	8 hours
France	8.75 hours
Poland	12 hours
United States	7 hours
Brazil	11.66 hours

vehicles recorded the data traffic every second together with some geospatial data, and the connections were registered in the form of connection events. The vehicles were left to drive around the city of Porto for six days. During this period, whenever Veniam's platform would establish a successful connection through the configured networks, *iperf*, using the OBU as client and server, was set to send traffic continuously whenever connected by Wi-Fi.

From the testbed, only four vehicles were available to perform such test; therefore two were set in the download mode, to evaluate the capacity of transferring data to the vehicle, while for the other two vehicles *iperf* was set into upload mode, where the performance of the solution for sending data from the vehicle to the cloud was under examination.

The expected download and upload data rates were obtained from this test, as well as the availability of Wi-Fi connectivity and time between connections. A further elaboration on these metrics is presented in the section below.

4.4 Analysis of the results

In Section 4.1 was mentioned that the vehicles used were part of a commercial fleet of buses. The driving times and distances of this fleet, as well as the driving behaviour, differ from the end-users using their private vehicles, where the usage is around commuting and leisure. For this purpose, to normalise the data and to make it meaningful for this thesis, the results were evaluated based on driving time, rather than by total time, and then compared to the average driving time.

In Table 4.4, the national averages for some countries are displayed. As a reference, the Portuguese driving time was used as the comparison to the tests, since the tests took place in Portugal. For the first test, where concrete use cases are tested, the time driven since the submission of the file until the conclusion of the transfer were measured under driving time for successful transfer, and then compared to the weekly average driving time, and obtain an expected normalised time to complete transfer and compare it to the delay tolerance.

For the second test, for the evaluation of the solutions' traffic capacity several results were assessed. Firstly, the expected throughput was obtained and compared to the required data rate for each application. From there, some use cases were already discarded. When the minimum required data rate was obtained, the delay tolerance followed to be evaluated, both from a technology perspective, through the minimum end-to-end latency obtainable through the usage of Wi-Fi, and by the time between connections to evaluate whether the solution warrants a connection within the delay tolerance limits. The distribution of the megabytes transferred per second during the test was obtained to provide a better understanding of the connectivity patterns and the inherent throughputs, as well as an expected value for the data rates. To measure the availability of the solution, the time connected to a Wi-Fi network was divided by the total driving time per vehicle.

The software *R* was used for the treatment of data resulting from both tests, and the results were summarised in the tables displayed in Chapter 5.

4.5 Cost analysis

One of the essential criteria, when evaluating a solution and comparing it to the options, is the inherent costs associated with that technology and the alternatives. Since C-V2X and DSRC are not deployed nor the infrastructure built, it is not yet possible to estimate the costs of data transfer through those solutions.

In Section 3.3 it was observed that while mobile plans are most commonly priced by GB, broadband plans have monthly flat rates with unlimited data volumes. It was also referred to some international services that provide deals for multiple geographies that aggregate different providers, or even free Wi-Fi networks.

For the use cases presented above, and considering a month as having 4 weeks, the total data transferred per month would amount to 4,290 GB. Considering the average price of 1GB of cellular broadband data in Portugal of $13.98 (Cable.co.uk, 2019), this would correspond to $59.97 per month, while it would be possible to acquire a FON license for a value of €24.90 per month, seen in Section 3.3, while making use of the public open Wi-Fi networks available in the big urban areas.

Considering now the average worldwide prices, where the price per GB of cellular broadband data is significantly lower than in Portugal, the total value per month would be $22.57 per month. Also in Section 3.3 it was mentioned that some worldwide packages offer yearly connectivity for $30.00 per vehicle, while the monthly FON license purchasable for €24.90 in Portugal can also be used to all the FON hotspots worldwide. The price paid using cellular broadband technologies is cheaper when compared to a monthly FON license, however, that is not the case for the yearly Wi-Fi aggregators fees.

It is important to underline that data needs are growing exponentially, as pointed out in Section 3.1, and therefore this is expected to grow in the future, where the price advantages of using Wi-Fi will be more significant due to the flat rate pricing models for this technology.

4.6 Performance comparison to alternatives

As part of the product analysis, the Wi-Fi-based solution for vehicle connectivity is compared to the available technologies that could be used for the same purpose. It was mentioned that it is not possible for now to compare with C-V2X and DSRC since the technologies are not mature enough to give visibility of their performances or costs. This comparison is, therefore, limited to cellular broadband network technologies, which in this case would be 4G, similarly to LTE, since 5G, too, is yet to be available.

Boyland (2019) provides an extensive overview of the global state of mobile network experience, based on 4G statistics around the world. The analysis conducted points to an 80% availability in the 87 analysed countries, with European countries ranking as the region with the best overall performances. The global average speed for those countries is 2.2 MB/s. For the context of this thesis, these values were used in the comparison of Wi-Fi obtained results and the cellular-based technologies.

When approaching the cost comparison between solutions, the ratio mentioned in the section above was taken into consideration.

Chapter 5

Results

In the present chapter, the measurements and results achieved through the methodology previously described are presented. All results are derived from the experimental tests performed in the conditions described and treated accordingly. This chapter, therefore, shows the relevant statistics that allow the analysis of the product given to the market as it currently is. The results are compared with the requirements and thresholds set. Firstly, in Section 5.1 the results of the delay-tolerant use cases test are displayed, followed by the results of the delay intolerant applications, that was separated into two subsections, the first for the download tests and the second for the upload tests. Finally, an analysis of the tests themselves and the unexpected situations encountered is made. For the course of this section, the vehicles used for the test will be referred to as OBU (on board unit).

5.1 Delay tolerant use cases results

Before analysing the results obtained for the delay-tolerant test, a short analysis of the driving behaviour of each vehicle was performed. In Table 5.1, it is possible to inspect the total driven hours, the active driving days and the average daily driven hours for the seven days during which the test took place. The standard behaviour of the vehicles was, whenever active and once started driving, driving continuously throughout the day without interruptions.

Table 5.1: Driving data from the OBUs used for the delay tolerant tests.

	Driven Hours	**Active driving days**	**Equivalent to 6.5 driven hours week**	**Average daily driven hours**
OBU 1	61h37m	5 days	9.5 weeks	12h19m24s
OBU 2	64h29m	5 days	9.9 weeks	12h53m48s
OBU 3	37h09m	6 days	5.71 weeks	6h11m30s
OBU 4	35h37m	5 days	5.5 weeks	7h07m30s
OBU 5	37h08m	3 days	5.7 weeks	12h22m40s

Table 5.2: Overview of the results achieved for each OBU.

	Connected time	**Percentage of Wi-Fi connected time**	**Total number of Wi-Fi connections**	**Median connection duration**	**Total file transfers**	**Successful file Transfers**	**Percentage of Successul file transfers**	**Percentage of planned successful file transfers**
OBU 1	06:56:52	11.3%	667	15 s	29	23	79.3%	71.9%
OBU 2	06:37:28	10.3%	803	15 s	32	26	81.3%	81.3%
OBU 3	04:40:33	12.6%	237	15 s	31	19	61.3%	59.4%
OBU 4	03:37:03	10.2%	382	15 s	32	21	65.6%	65.6%
OBU 5	05:40:39	15.3%	129	18 s	26	13	50.0%	40.6%

As mentioned in the previous section, these vehicles have longer driving hours than a regular private vehicle, where, in Porto, the expected driving time per week is 6.5 hours. Analysing the average daily driven time, it was noticeable that vehicles can do up to two times that value in only one active day of driving. It was also necessary to consider these factors when analysing the capacity of Veniam's platform to transfer files within the allowed delay tolerance. For this purpose, the driven hours were converted to the equivalent time for regular private vehicle usage, seen under the variable "Equivalent to 6.5 driving hours week". This variable can be interpreted as follows: taking the example of OBU, where the vehicle drove, during the test, 61 hours and 37 minutes, the week is equivalent to 9.5 weeks of driving, and in this case, a full day of driving for OBU 1 equals 1.9 weeks of driving for the average user.

The results for the first test were analysed under two perspectives; firstly, from a vehicle perspective, where the results achieved for each OBU are analysed, and secondly, the results for each use case are presented and interpreted, as well an investigation of the possible causes for the results.

In Table 5.2, an overview of the results for the delay-tolerant test is displayed. First, some connection data is presented, such as total connected time, percentage of Wi-Fi connected time, the total number of Wi-Fi connections and the median duration of connection for each vehicle. From the 32 planned file transfers, there were a few V2C (Vehicle to Cloud) files that could not be sent during this period due to the inactivity and offline status of the vehicles. This was especially the case for OBU 5, where the vehicle was inactive and inaccessible for four days. The variable Total file transfers provides additionally the information of the number of files planned that could not be sent, where, as an example, OBU 5, the one with the lowest number of active days, had only 26 out of 32 sent files. The total number of those that were sent and successfully received are displayed as the successful file transfers. A successful transfer is a transfer that was successfully sent or received within the delay tolerance. The percentage of the successful files transfers is relative to the number of actual files sent or received, while the percentage of successfully planned file transfers is the number of successful file transfers divided by the 32 initially planned transfers.

As mentioned, due to the lower inactivity of OBU 5, it is expected that this OBU presents lower success rates, since it was not online and, therefore, not connected to Wi-Fi to receive the files. This offered a particular impediment to files with lower delay tolerances, such as the urgent software update or the recurring dynamic map updates, that admit only 36 minutes of delay tolerance. It is imperative to underline that cases such as predictive maintenance or usage based insurance data files, each possess unique valuable information that is essential to be received.

Table 5.3: Results and performance by use case.

	Planned transfers	**Actual transfers**	**Successful transfers**	**Success rate**	**Success rate of planned transfers**	**Average transfer attempts**	**Average successful transfer attempts**	**Average duration for successful transfer**
Software update (urgent)	5	5	0	0.0%	0.0%	-	-	-
Software update (not urgent)	5	5	4	80.0%	80.0%	384.8	140.5	2 days 10h07m35s
Basic map update	5	5	5	100.0%	100.0%	167.8	46.2	1 day 07h19m30s
Unit configuration update	5	5	5	100.0%	100.0%	7.8	3.4	04h01m16a
Dynamic map updates	70	70	33	47.1%	47.1%	8.6	1.1	08m10s
Usage Based Insurance	35	32	29	90.6%	82.8%	7.3	1.7	05h54m27s
Predictive Maintenance	35	28	28	100%	80.0%	2.3	1.3	02h15m23s

Oppositely, the dynamic map updates become obsolete once a new one is sent; therefore, when the vehicle is not being used, there is no necessity for the dynamic map updates for that period. Hence, it was expected that the success rate for this case was rather low, and its interpretation should not be the same as in the first case mentioned.

In Table 5.3, a more in-depth analysis of the specific use case can be found. The first columns present the number of planned, actual transfers and the number of successful transfers. The success rate is the percentage obtained by diving the successful transfers by the actual transfers, while the success rate of planned transfers is the same percentage by the number of planned transfers. Considering the dynamic map updates forthwith, less than half were successfully transferred. As underlined above, it is relevant to understand the cause for the unsuccessful transfers, since in case the vehicle was not active for that period, the failed transfer becomes irrelevant. If, however, the vehicle was driving during that period and unable to connect to Wi-Fi for the needed time and frequency, the situation becomes relevant to measure the Wi-Fi suitability for this use case. From the 37 failed transfers, 24 were during vehicle inactivity days, with the remaining 13 being while the vehicles were driving. In this case, 46 of the 70 planned transfers should be considered relevant, and if used to measure the success rate, the value increases to 71.7%.

The average transfer attempts is the number of times the OBU was connected to Wi-Fi and tried to transfer the file for a successful transfer, whereas the average successful transfer attempts refer to only those where some data was sent. Every time the OBU is connected to Wi-Fi, there is an attempt to transfer the file at the top of the queue. The average total attempts can be seen as the connectivity opportunities needed to transfer the file successfully.

It is possible to observe that for the use case of the urgent software update, with a delay tolerance of 3 hours, none of the attempts was successful. For OBU 5, it was sent while it was inactive, and the download was consequently not started, while for the other 4 OBUs, on average, 10% of the 3GB was downloaded. The test hints that Wi-Fi might not be a suitable technology for such use cases. Some conclusions can already be drawn while analysing the average duration

Table 5.4: Driving data from the OBUs used for the delay intolerant tests.

	Test direction	**Driven Hours**	**Driven Days**
OBU 1	Download	44h00m	5 days
OBU 2	Download	45h47m	5 days
OBU 3	Upload	6h45m	1 day
OBU 4	Upload	7h41m	1 day

for a successful transfer. Considering one week of delay tolerance, which for regular vehicles is about 6h30min of driving, even for the vehicle with the lowest number of hours driven per day, a duration longer than one day for each use case would be beyond the allowed limit. Considering the not urgent software updates, that were sent only in days where the vehicle was active, these took close to 2.5 days, which goes beyond the equivalent 6.5 hours of drive per week. The same is observed for the basic map updates, despite the higher success rate. This points to a possible failure for that use case for the typical individual user scenarios.

The remaining use cases, unit configuration update, usage based insurance and predictive maintenance seem to be within the defined limits. Some of the usage based insurance transfers were not failed, but somewhat incomplete, since the files were sent up to 2 days before the end of the test, and having some inactivity in between.

5.2 Delay intolerant use cases results

In Table 5.4 the driving behaviour of the vehicles used for delay intolerant test is displayed, as well as the direction of traffic for each. The first two OBUs were used for download and the last two for upload. Coincidently, for the upload OBUs, only data from the first day was available, and the remaining seemed to have not been recorded for unknown reasons.

Analysing first the download capacity of Veniam's product, Table 5.5 displays the results obtained for download traffic, as well as some other useful metrics for evaluation of the performance. Throughout the seven days of tests, the vehicles presented around 11% of connected time to Wi-Fi while driving, and a median connection duration of 15 seconds. The total number of connections during that time was for both around 550, to about 150 distinct Access Points in both cases, which is expected since the vehicles usually drive around the same routes. The average throughput and time between connections will be used to compare the performance to the applications' requirements.

Table 5.5: Results obtained for the download test.

	Data Downloaded	**Total Connected Time**	**Percentage of Wi-Fi connected time**	**Median Connection Duration**	**Total number of connections**	**Total distinct APs**	**Average Throughput**	**Average time between connections**
OBU 1	22.743 GB	4h36m17s	10.46%	15 seconds	535	154	1.38 MB/s	5min10s
OBU 2	13.892 GB	5h25m06s	11.84%	15 seconds	566	162	0.70 MB/s	5min27s

Table 5.6: Performance by Wi-Fi network for OBU 1 and 2.

OBU 1	Total Connections	Percentage of Connections	Downloaded Data	Connected Time	Data Rate (MBs)
WiFi Porto Digital	153	47.0%	20.855 MB	2h09min49s	2.68
NOS_WIFI_Fon	171	35.0%	589 MB	1h36min32s	0.10
Veniam (Test)	43	10.8 %	1.192 MB	29min58s	0.66
MEO-WiFi	21	7.2%	107 MB	19min58s	0.09
TOTAL	388	-	22.743 MB	4h36min17s	1.38

OBU 2	Total Connections	Percentage of Connected time	Downloaded Data	Connected Time	Data Rate (MBs)
WiFi Porto Digital	73	37.9%	11.254 MB	2h03min05s	1.52
NOS_WIFI_Fon	177	39.0%	985 MB	2h06min52s	0.13
Veniam (Test)	54	14.4%	1.423 MB	46min59s	0.055
MEO-WiFi	42	8.7%	231 MB	28min11s	0.14
TOTAL	346	-	13.892 MB	5h25min06s	0.7

There is, however, a significant difference in the total data downloaded from both cases, despite the similarity of connected times. As an attempt to bring some further understanding to causes for this situation, the connections were delved into with more detail to justify the difference. When analysing Table 5.6, there is a clear difference in the connections per network. OBU 2 has a majority of its connections to NOS_WIFI_Fon, a network that, as mentioned in Section 4.1, has a limited data rate of 2 MB/s. In contrast, OBU 1 has significantly more connections to Wi-Fi Porto Digital, an unlimited data rate outdoor network of hotspots provided by the city. This network represents for both of the OBUs the highest percentage of downloaded data, with 91.6% for OBU 1 and 81% for OBU 2, and a much higher data rate per minute, reaching values 32 times higher than NOS_WIFI_Fon. It is suggested that the difference in the volumes downloaded might come from the connection opportunities to the network Wi-Fi Porto Digital for both OBUs. A reinforcement of this hypothesis comes from the analysis of the routes from both OBUs, in Figure 5.1. It is possible to identify the similarities in the routes, where both drove through Estrada da Circunvalação, from Praça de Gonçalves Zarco in Foz to the Campanhã Train Station. However, OBU 1 seems to have visited additionally the city centre of Porto, where the network Wi-Fi Porto Digital can be found more often.

In Table 5.7 the upload results are presented. Despite the considerable difference in the available data, it is possible to compare the results obtained to each other. The percentage of connected time is also higher than on the tests above, but that might be caused by choice of route of that day, and the effect is not as diluted due to the smaller sample size. The median connection duration is about the same, and the data rate volumes are quite different, with 1.26 MB/s and 0.46 MB/s. This might be prompted by the higher number of connections, and the fact that possibly the bus was stopped for an abnormal period, however, it is not possible to identify the cause for such difference.

Figure 5.1: Routes for OBU 1 (in blue) and for OBU 2 (in green) during the course of the tests.

For the evaluation of the traffic capacity of Veniam's platform, the average throughputs, and the average time between connections were taken into consideration to compare with the required data rates and delay tolerance. As such, the considered upload capacity will be the weighted average of the throughout, resulting in a value of 0.934 MB/s. For the download, using the same reasoning, the weighted average throughput is 1.0 MB/s. As for the time between connections, a weighted average of the values achieved by each vehicle is calculated, with a value of 4min52s. The time between connections was used to evaluate the capacity to provide the required levels of latency. This variable was used since, from a technological point of view, Wi-Fi 6 is able to provide the required levels of end-to-end latency for continuous connections for most cases, exceptions being the tele-operated driving and cooperative sensing. The constraints of using Wi-Fi in such scenarios lay on the intermittent short nature of its connections. Through these connections it is not possible to ensure a continuous flow of the data within the needed delay tolerance. To evaluate the reliability levels achievable by a Wi-Fi based solution, the variable Wi-Fi availability, considering the total time connected divided by the total driving time, was measured and used. A summary of the values considered is visible in Table 5.8.

Such values excluded most cases at the end of Table 3.2, that accept values of latency lower than 4mins52s second and reliabilities higher than 12.3%. The exceptions are music streaming and video streaming, where the delay tolerance goes up to 5 minutes. The experimental value achieved of 4min52s falls by a narrow margin within the set interval and the data rates obtained

Table 5.7: Results obtained for the upload test.

	Data Uploaded	**Total Connected Time**	**Percentage of Wi-Fi connected time**	**Median Connection Duration**	**Total Number of Connections**	**Total distinct APs**	**Average Throughput**	**Average time between connections**
OBU 3	2.490 GB	1h18m54s	19.46%	15 seconds	41	21	0.46 MB/s	2m10s
OBU 4	8.704 GB	1h54m01s	24.72%	15 seconds	133	40	1.26 MB/s	2m07s

Table 5.8: Experimental values considered for comparison with the requirements of the delay intolerant applications.

Download Data rate	**Upload Data rate**	**Time between connections**	**Wi-Fi availability**
1 MB/s	0.93 MB/s	4min52s	12.3%

surpass the ones required. This implies that such use cases might be able to be fulfilled using Wi-Fi, depending on the buffer and cache policies and limits of the platforms used for streaming.

Chapter 6

Conclusion

The present chapter, as last of this dissertation, serves as a conclusion to the dissertation and as discussion of the results presented in the previous chapter. In the first section, a brief interpretation of the results obtained and a description of the main discoveries is made, together with some recommendations for future work. The last section of this thesis contains the implications for practice and for Veniam, and suggests the topic of Heterogenous Vehicular Networks for further investigation in the future.

6.1 Discussion and main findings

Overall, the results of this dissertation suggest that delay tolerant applications can be covered using the Veniam's platform, while the delay intolerant use cases are quite limited by the intermitted connections and the percentage of connected time on the values of above 12%. Technologically speaking, Wi-Fi 6 matches the needed requirements for vehicular connectivity, with very high data rates and the lowest achievable latencies below 0,12ms. However, the values of availability obtained translate in the inability to fulfil the stipulated reliabilities above 90% and therefore, ensuring the service levels for security applications and autonomous vehicle operations. This is not the case for music and video streaming, where the values obtain are within the set limits, however by a short margin, having an impact on the quality of service enjoyed by the end customer. An appealing hypothesis lies on the increase of the allowed latency for music and video streaming, which in this case translates into songs in cache and video buffer, where if the platform and content providers allow a larger download of buffer and cache when connected to Wi-Fi networks, Wi-Fi could present a compelling solution for such use cases.

Due to the difference in pricing, where in most cases, Wi-Fi has a flat monthly rate with unlimited access, while in most cases cellular broadband technologies have pricing models based on the volume of data used, Wi-Fi presents a clear advantage for cases with higher volumes of monthly data used. The information gathered during the course of this dissertation suggest, however, that Wi-Fi is confirmed to be cheaper than the competing technologies, therefore, possibly posing as an option to be used as frequently as possible and as a complementing technology to a solution making use of multiple connectivity options. However, data plans are not yet made considering such cases, therefore, cooperation with telecommunication providers might be beneficial for companies such as Veniam.

The technological landscape is, nonetheless, fast changing and quickly presenting new developments, making it essential to continually evaluate the several possibilities. C-V2X could be introduced soon in the market and the mass deployment of 5G could deliver disruptive changes to these conclusions and findings.

Some of the conditions under which the tests were performed were not ideal, such as using a commercial fleet of buses to test the solution. These have more stops and drive for longer than usual with lower average speeds, changing the connectivity conditions and as a result, possibly impacting the results obtain. Another limitation was the data lost for the upload test, that affected the quality of the conclusions on the upload capacity. Since these results are limited to cities with characteristics similar to the city of Porto, the same results might not be observed in other locations. All these factors recommend that, once there is that possibility, repeating the tests with private vehicles in higher number, driving in different geographies and city types and under different conditions might be beneficial to confirm the results obtain throughout this dissertation.

The difference in the results obtained for each OBU in the test intolerant data brings us many conclusions. Different routes from the buses had different connectivity levels mainly due to the access of different hotspots and hotspots types. It was possible to observe that the best performing hotspot for all cases was WiFi Porto Digital, which consist of outdoor open hotspots. These connections are longer and present higher transferred data volumes. The second best performing network was Veniam (Test), a private password protected network, with the hotspot networks from the providers coming last. Networks such as WiFi Porto Digital are available in larger urban regions, with a higher density of hotspots in the city centres. As a future work, it would be interesting to analyse the impact of chosen routes in the connectivity levels, as well as variations according the locations of those routes (for example, comparing routes on cities' outskirts with routes in city centres). This underlines the impact that governments and cities can have in creating better connectivity conditions for vehicles and creating connected environments.

Another conclusion that is drawn from those same results is the impact of the hotspot availability in the connectivity levels. Countries and cities with a higher density and availability of access point will reflect higher connected times and volumes of data, therefore the suitability of Wi-Fi as a technology for vehicle connection will also have different values for different locations. Considering countries such as Mauritania or Papua New Guinea, where the infrastructure for broadband internet connections is not yet built making Wi-Fi connectivity extremely expensive and rare (average broadband prices are respectively \$571,67 and \$768,16 per month and there about 4600 and 580 free Wi-Fi networks at each country reported in Wiman (2020)). A Wi-Fi based solution would not be beneficial, at the time being, for such geographies.

As a final remark to the impact of locations and conditions, vehicles that are parked in locations within the range of a Wi-Fi network, such as garages or private residences, will be the ones to benefit from Wi-Fi based solutions the most, since for some minutes after the car is parked and the OBU remains sleeping there is still the capacity to connect and transfer.

6.2 Implications for practice

In the section above it was concluded that a Wi-Fi based solution is indeed suitable and more beneficial for some use cases and in some cases and locations, where for those applications it is possible to rely only in Wi-Fi as a technology. This is, however, not enough to cover all the use cases and needs of the market, already as they are now.

It was also possible to observe in Section 2.6 that different technologies pose different advantages and, as a result, might also represent a better connectivity solution for some cases. In this context, it is interesting to investigate solutions leveraging more than one technology for connecting vehicles.

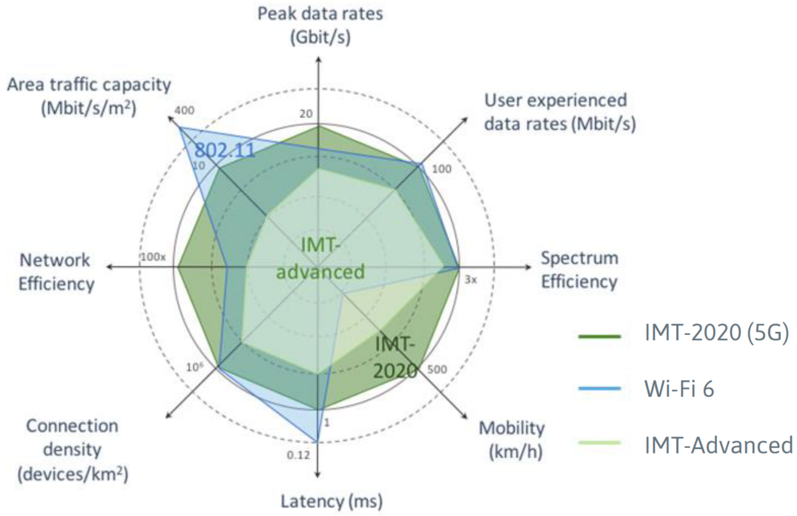
This is a concept already explored under the label of Heterogenous Vehicular Networks (HetVNETs) that so far, as been explored under the scope of using cellular networks with DSRC, as done by Zheng et al. (2015) and by Hagenauer et al. (2014) with a broader scope encompassing Wi-Fi.

In HetVNETs, most of the technologies approached in Chapter 2 could be considered simultaneously, optimising the assets while neutralising the vulnerabilities of each.

When also considering other technologies and utilising Wi-Fi as much as possible, it is possible to ensure transfer within the delay tolerances and the required reliabilities, while offloading some of the data through Wi-Fi. Wi-Fi offload is a concept already described for other contexts, mainly around mobile phones, where Wi-Fi is used to increase the connectivity capacity and relieve the congestion around cellular broadband technologies (Balasubramanian et al., 2010). Taking as example the urgent software update, the achieved average download percentage of 10% of the 3GB in the allowed time would be still downloaded through Wi-Fi while the remaining 90% downloaded through cellular broadband technologies or another chosen technology. This could save costs, support faster transfers, and higher connection availability, as exposed in Section 4.6.

On a Wireless Broadband Alliance report on the industry, Fellah and Gabriel (2019) underline the importance of using 4G and 5G technologies, alongside Wi-Fi to complement each other, since they all serve as best solution for different cases. In Figure 6.1, it is possible to observe that Wi-Fi 6 presents the highest area traffic capacity and the lowest values for latency, when compared to 4G and 5G, represented as IMT-Advanced and IMT-2020 respectively. Between 4G and 5G, despite not being represented in the figure, 4G presents a better range per antenna, around 30km of range, while 5G is predicted to have a range of not even 1km due to much higher frequencies bands at which it operates. This will also make 5G more expensive than 4G. 5G outperforms 4G in all remaining variables. When approaching the comparison of 5G with Wi-Fi, 5G offers a higher mobility, where devices can move at up to 500km/h with higher network efficiencies.

Literature on this topic is, however, not common, and most of the significant papers are dating to 2016. Since then, new developments have occurred and emerged in the ecosystem, including



Source: WBA 5G Work Group

Figure 6.1: Capabilities of 802.11ax, compared to LTE Advanced and 5G. Source: (Wireless Broadband Alliance, 2017)

the introduction of new technologies and new disruptive generations to the already existing ones. A recommendation from this dissertation is also that some further investigation into HetVNETs should be done, to consider the usage of multiple technologies.

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Appendix A

Worldwide Mobile Data Pricing

In Table A.1, the average price of 1GB in 230 countries can be seen. This table divides the countries in Continental regions, and also includes the number of plans measured from different countries dated with a sample date. It is also possible see the minimum and maximum price per GB for each country. The prices are in USD, with the exchange rate applied from 02.02.2019.

Rank	**Name**	**Continental region**	**Plans measured**	**Average price of 1GB**	**Cheapest 1GB**	**Most expensive 1GB**	**Sample date**
1	India	ASIA (EX. NEAR EAST)	57	$0.26	$0.02	$1.40	09/11/2018
2	Kyrgyzstan	CIS (FORMER USSR)	12	$0.27	$0.08	$0.48	12/11/2018
3	Kazakhstan	CIS (FORMER USSR)	26	$0.49	$0.28	$0.79	12/11/2018
4	Ukraine	CIS (FORMER USSR)	12	$0.51	$0.21	$1.38	29/10/2018
5	Rwanda	SUB-SAHARAN AFRICA	36	$0.56	$0.04	$2.78	19/11/2018
6	Sudan	SUB-SAHARAN AFRICA	35	$0.68	$0.29	$1.63	19/11/2018
7	Sri Lanka	ASIA (EX. NEAR EAST)	38	$0.78	$0.22	$2.09	12/11/2018
8	Mongolia	ASIA (EX. NEAR EAST)	26	$0.82	$0.41	$2.26	13/11/2018
9	Myanmar	ASIA (EX. NEAR EAST)	11	$0.87	$0.65	$1.48	13/11/2018
10	Congo (Democratic Republic of)	SUB-SAHARAN AFRICA	31	$0.88	$0.05	$5.05	06/11/2018
11	Israel	NEAR EAST	25	$0.90	$0.11	$6.89	09/11/2018
12	Russian Federation	CIS (FORMER USSR)	31	$0.91	$0.14	$2.19	19/11/2018
13	Bangladesh	ASIA (EX. NEAR EAST)	53	$0.99	$0.18	$3.81	29/10/2018
14	Finland	WESTERN EUROPE	20	$1.16	$0.30	$2.17	24/10/2018
15	Malaysia	ASIA (EX. NEAR EAST)	60	$1.18	$0.24	$3.27	13/11/2018
16	Monaco	WESTERN EUROPE	3	$1.21	$0.90	$1.70	29/10/2018
17	Indonesia	ASIA (EX. NEAR EAST)	60	$1.21	$0.13	$4.25	09/11/2018
18	Bhutan	ASIA (EX. NEAR EAST)	37	$1.25	$0.51	$2.72	06/11/2018
19	Iran	ASIA (EX. NEAR EAST)	36	$1.28	$0.38	$4.75	09/11/2018
20	Vietnam	ASIA (EX. NEAR EAST)	41	$1.31	$0.06	$6.45	25/10/2018
21	Poland	EASTERN EUROPE	57	$1.32	$0.13	$5.21	16/11/2018
22	Denmark	WESTERN EUROPE	24	$1.36	$0.36	$4.52	30/10/2018
23	Cambodia	ASIA (EX. NEAR EAST)	36	$1.49	$0.17	$6.25	26/11/2018
24	Egypt	NORTHERN AFRICA	37	$1.49	$0.48	$4.55	23/10/2018
25	Ghana	SUB-SAHARAN AFRICA	54	$1.56	$0.34	$4.75	08/11/2018
26	Afghanistan	ASIA (EX. NEAR EAST)	46	$1.60	$0.66	$3.96	24/10/2018
27	Armenia	CIS (FORMER USSR)	29	$1.65	$0.61	$3.07	24/10/2018
28	Morocco	NORTHERN AFRICA	34	$1.66	$0.58	$5.25	05/11/2018
29	Western Sahara	NORTHERN AFRICA	34	$1.66	$0.58	$5.25	27/11/2018

Table A.1 continued from previous page

Rank	Name	Continental region	Plans measured	Average price of 1GB	Cheapest 1GB	Most expensive 1GB	Sample date
30	Cameroon	SUB-SAHARAN AFRICA	36	$1.71	$0.34	$6.89	26/10/2018
31	Italy	WESTERN EUROPE	44	$1.73	$0.18	$11.31	12/11/2018
32	Jordan	NEAR EAST	49	$1.79	$0.42	$5.99	09/11/2018
33	Pakistan	ASIA (EX. NEAR EAST)	58	$1.85	$0.29	$7.15	16/11/2018
34	Chile	SOUTH AMERICA	60	$1.87	$0.73	$6.05	07/11/2018
35	Dominican Republic	CARIBBEAN	9	$1.88	$1.42	$3.12	07/11/2018
36	Austria	WESTERN EUROPE	59	$1.88	$0.28	$11.08	25/10/2018
37	Romania	EASTERN EUROPE	19	$1.89	$0.13	$4.90	19/11/2018
38	Guinea	SUB-SAHARAN AFRICA	27	$1.94	$1.20	$2.64	08/11/2018
39	Burundi	SUB-SAHARAN AFRICA	31	$2.00	$0.37	$3.70	15/02/2019
40	Kuwait	NEAR EAST	36	$2.01	$0.06	$11.52	12/11/2018
41	Lithuania	BALTICS	11	$2.06	$0.63	$4.81	08/11/2018
42	Palestine, State of	NEAR EAST	30	$2.06	$0.20	$9.19	16/11/2018
43	Slovenia	EASTERN EUROPE	28	$2.21	$0.08	$10.17	20/11/2018
44	Nigeria	SUB-SAHARAN AFRICA	57	$2.22	$0.26	$13.79	14/11/2018
45	Nepal	ASIA (EX. NEAR EAST)	27	$2.25	$0.32	$6.43	15/11/2018
46	Zambia	SUB-SAHARAN AFRICA	45	$2.25	$0.42	$8.44	22/11/2018
47	Turkey	NEAR EAST	56	$2.25	$0.58	$15.82	21/11/2018
48	Belarus	CIS (FORMER USSR)	25	$2.36	$0.31	$7.97	31/10/2018
49	Lesotho	SUB-SAHARAN AFRICA	30	$2.43	$0.68	$7.56	29/10/2018
50	Australia	OCEANIA	56	$2.47	$0.11	$7.59	25/10/2018
51	Peru	SOUTH AMERICA	23	$2.48	$1.57	$3.35	15/11/2018
52	Réunion	SUB-SAHARAN AFRICA	12	$2.51	$0.41	$15.82	19/11/2018
53	Azerbaijan	CIS (FORMER USSR)	35	$2.69	$0.23	$9.38	25/10/2018
54	Kenya	SUB-SAHARAN AFRICA	54	$2.73	$0.28	$9.97	12/11/2018
55	Thailand	ASIA (EX. NEAR EAST)	59	$2.78	$0.80	$9.58	21/11/2018
56	Uruguay	SOUTH AMERICA	41	$2.80	$0.40	$10.73	22/11/2018
57	Moldova	EASTERN EUROPE	15	$2.82	$0.78	$8.76	08/11/2018

Table A.1 continued from previous page

Rank	Name	Continental region	Plans measured	Average price of 1GB	Cheapest 1GB	Most expensive 1GB	Sample date
58	Bahrain	NEAR EAST	20	$2.83	$1.81	$7.96	05/11/2018
59	Tunisia	NORTHERN AFRICA	37	$2.87	$0.31	$13.42	21/11/2018
60	Ethiopia	SUB-SAHARAN AFRICA	8	$2.91	$2.11	$3.86	26/10/2018
61	Niger	SUB-SAHARAN AFRICA	45	$2.92	$1.38	$14.36	14/11/2018
62	France	WESTERN EUROPE	49	$2.99	$0.17	$19.21	30/10/2018
63	Guernsey	WESTERN EUROPE	23	$3.05	$0.48	$25.85	08/11/2018
64	Argentina	SOUTH AMERICA	36	$3.05	$0.65	$10.59	23/10/2018
65	Åland Islands	WESTERN EUROPE	6	$3.10	$1.13	$8.42	25/10/2018
66	Mauritania	NORTHERN AFRICA	14	$3.12	$1.22	$7.83	13/11/2018
67	Philippines	ASIA (EX. NEAR EAST)	19	$3.16	$0.95	$7.64	16/11/2018
68	Albania	EASTERN EUROPE	33	$3.22	$0.68	$13.18	24/10/2018
69	Uzbekistan	CIS (FORMER USSR)	56	$3.27	$0.43	$11.89	22/11/2018
70	Senegal	SUB-SAHARAN AFRICA	21	$3.28	$0.29	$13.79	20/11/2018
71	Georgia	CIS (FORMER USSR)	36	$3.33	$0.32	$18.98	08/11/2018
72	Madagascar	SUB-SAHARAN AFRICA	26	$3.39	$0.80	$8.39	26/10/2018
73	Lao PDR	ASIA (EX. NEAR EAST)	37	$3.42	$0.29	$4.65	12/11/2018
74	Brazil	SOUTH AMERICA	27	$3.50	$1.50	$10.18	06/11/2018
75	Fiji	OCEANIA	14	$3.57	$0.47	$18.40	30/10/2018
76	Bosnia and Herzegovina	EASTERN EUROPE	20	$3.58	$0.49	$7.78	25/10/2018
77	Malawi	SUB-SAHARAN AFRICA	18	$3.59	$1.37	$7.51	13/11/2018
78	Macedonia	EASTERN EUROPE	37	$3.62	$0.57	$18.24	02/11/2018
79	Sweden	WESTERN EUROPE	58	$3.66	$0.37	$15.91	20/11/2018
80	Estonia	BALTICS	31	$3.67	$0.45	$18.09	26/10/2018
81	Singapore	ASIA (EX. NEAR EAST)	37	$3.67	$0.37	$9.34	02/11/2018
82	Mauritius	SUB-SAHARAN AFRICA	11	$3.71	$1.75	$6.98	13/11/2018
83	Liberia	SUB-SAHARAN AFRICA	35	$3.75	$0.60	$12.50	13/11/2018
84	Iceland	WESTERN EUROPE	23	$3.78	$0.26	$14.19	02/11/2018
85	Spain	WESTERN EUROPE	56	$3.79	$0.77	$10.55	01/11/2018

Table A.1 continued from previous page

Rank	Name	Continental region	Plans measured	Average price of 1GB	Cheapest 1GB	Most expensive 1GB	Sample date
86	Jersey	WESTERN EUROPE	30	$3.82	$0.52	$25.85	30/10/2018
87	Ireland	WESTERN EUROPE	24	$3.95	$0.65	$22.61	29/10/2018
88	Hong Kong	ASIA (EX. NEAR EAST)	51	$4.00	$1.01	$16.31	08/11/2018
89	Côte d'Ivoire	SUB-SAHARAN AFRICA	11	$4.10	$2.30	$6.89	06/11/2018
90	Syria	NEAR EAST	29	$4.14	$0.51	$15.76	20/11/2018
91	Cape Verde	SUB-SAHARAN AFRICA	13	$4.25	$2.56	$10.22	07/11/2018
92	Montenegro	EASTERN EUROPE	13	$4.26	$0.64	$6.16	07/11/2018
93	Luxembourg	WESTERN EUROPE	17	$4.39	$0.45	$11.31	08/11/2018
94	Timor-Leste	ASIA (EX. NEAR EAST)	25	$4.48	$2.50	$9.09	21/11/2019
95	Guatemala	CENTRAL AMERICA	19	$4.53	$1.43	$7.24	08/11/2018
96	El Salvador	CENTRAL AMERICA	27	$4.55	$1.33	$10.50	21/11/2018
97	Belize	CENTRAL AMERICA	34	$4.57	$2.56	$7.43	06/11/2018
98	Qatar	NEAR EAST	21	$4.62	$1.10	$13.73	19/11/2018
99	Jamaica	CARIBBEAN	23	$4.64	$1.86	$7.43	09/11/2018
100	Burkina Faso	SUB-SAHARAN AFRICA	34	$4.69	$1.72	$11.49	06/11/2018
101	Uganda	SUB-SAHARAN AFRICA	51	$4.69	$0.88	$13.60	22/11/2018
102	Serbia	EASTERN EUROPE	36	$4.83	$0.34	$23.95	19/11/2018
103	Tajikistan	CIS (FORMER USSR)	34	$4.84	$1.05	$15.86	21/11/2018
104	Macau	ASIA (EX. NEAR EAST)	39	$4.84	$1.78	$8.40	26/10/2018
105	Libya	NORTHERN AFRICA	13	$4.87	$1.20	$10.79	08/11/2018
106	Croatia	EASTERN EUROPE	38	$4.89	$0.46	$30.52	08/11/2018
107	Czech Republic	EASTERN EUROPE	22	$4.91	$1.76	$8.78	29/10/2018
108	Sint Maarten	CARIBBEAN	26	$4.92	$1.11	$19.35	20/11/2018
109	Vanuatu	OCEANIA	16	$4.94	$3.39	$6.32	02/11/2018
110	Guinea-Bissau	SUB-SAHARAN AFRICA	7	$4.96	$2.10	$11.49	08/11/2018
111	American Samoa	OCEANIA	11	$4.97	$3.89	$6.67	24/10/2018
112	Honduras	CENTRAL AMERICA	16	$5.02	$2.48	$10.00	29/10/2018
113	Costa Rica	CENTRAL AMERICA	18	$5.04	$2.72	$8.72	23/10/2018

Table A.1 continued from previous page

Rank	**Name**	**Continental region**	**Plans measured**	**Average price of 1GB**	**Cheapest 1GB**	**Most expensive 1GB**	**Sample date**
114	Algeria	NORTHERN AFRICA	21	$5.15	$0.48	$25.22	31/10/2018
115	Brunei Darussalam	ASIA (EX. NEAR EAST)	9	$5.25	$2.29	$14.81	06/11/2018
116	Maldives	ASIA (EX. NEAR EAST)	16	$5.27	$2.59	$12.95	29/10/2018
117	Colombia	SOUTH AMERICA	57	$5.28	$0.72	$15.93	07/11/2018
118	Gambia	SUB-SAHARAN AFRICA	20	$5.33	$2.45	$9.08	25/10/2018
119	São Tomé and Príncipe	SUB-SAHARAN AFRICA	19	$5.33	$1.38	$15.34	20/11/2018
120	Panama	CENTRAL AMERICA	29	$5.56	$2.00	$8.33	26/10/2018
121	Slovakia	EASTERN EUROPE	32	$5.56	$0.82	$33.92	06/11/2018
122	Saudi Arabia	NEAR EAST	42	$5.62	$0.38	$19.99	26/10/2018
123	Congo	SUB-SAHARAN AFRICA	41	$5.63	$1.23	$12.64	07/11/2018
124	Sierra Leone	SUB-SAHARAN AFRICA	13	$5.79	$3.49	$10.66	20/11/2018
125	Gabon	SUB-SAHARAN AFRICA	10	$5.84	$1.72	$13.26	25/10/2018
126	Tanzania	SUB-SAHARAN AFRICA	40	$5.93	$0.43	$53.76	21/11/2018
127	Northern Mariana Islands	OCEANIA	22	$5.99	$1.74	$20.00	13/11/2018
128	Central African Republic	SUB-SAHARAN AFRICA	11	$6.03	$2.87	$8.62	07/11/2018
129	Nicaragua	CENTRAL AMERICA	32	$6.04	$2.45	$19.59	16/11/2018
130	Guadeloupe	CARIBBEAN	9	$6.06	$0.90	$15.83	09/11/2018
131	Suriname	SOUTH AMERICA	23	$6.08	$1.91	$19.50	30/10/2018
132	Paraguay	SOUTH AMERICA	30	$6.18	$2.47	$19.80	19/11/2018
133	Somalia	SUB-SAHARAN AFRICA	24	$6.19	$1.60	$16.67	20/11/2018
134	Isle of Man	WESTERN EUROPE	14	$6.42	$0.90	$41.36	02/11/2018
135	Hungary	EASTERN EUROPE	18	$6.56	$1.51	$10.97	26/11/2018
136	United Kingdom	WESTERN EUROPE	60	$6.66	$0.26	$56.87	07/11/2018
137	San Marino	WESTERN EUROPE	6	$6.86	$1.54	$9.19	20/11/2018
138	Bahamas	CARIBBEAN	16	$6.89	$2.00	$11.19	23/10/2018
139	Ecuador	SOUTH AMERICA	18	$6.93	$0.65	$20.00	26/10/2018
140	Germany	WESTERN EUROPE	58	$6.96	$1.88	$22.60	23/10/2018
141	Latvia	BALTICS	13	$7.12	$2.09	$19.22	05/11/2018

Table A.1 continued from previous page

Rank	Name	Continental region	Plans measured	Average price of 1GB	Cheapest 1GB	Most expensive 1GB	Sample date
142	Bulgaria	EASTERN EUROPE	26	$7.15	$0.58	$37.54	05/11/2018
143	South Africa	SUB-SAHARAN AFRICA	58	$7.19	$0.71	$35.06	22/11/2018
144	Barbados	CARIBBEAN	35	$7.21	$1.83	$18.52	30/10/2018
145	Guyana	SOUTH AMERICA	25	$7.24	$4.09	$13.58	08/11/2018
146	Mexico	CENTRAL AMERICA	57	$7.38	$2.06	$34.63	14/11/2018
147	Saint Barthélemy	CARIBBEAN	17	$7.40	$0.56	$21.48	30/10/2018
148	Faroe Islands	WESTERN EUROPE	7	$7.77	$1.15	$33.19	29/10/2018
149	Haiti	CARIBBEAN	24	$7.91	$0.46	$29.56	09/11/2018
150	Angola	SUB-SAHARAN AFRICA	13	$7.95	$1.91	$15.90	06/11/2018
151	The Netherlands	WESTERN EUROPE	41	$7.99	$0.90	$37.69	14/11/2018
152	Iraq	NEAR EAST	24	$8.00	$1.46	$20.07	09/11/2018
153	Palau	OCEANIA	7	$8.34	$3.13	$16.00	19/11/2018
154	Japan	ASIA (EX. NEAR EAST)	60	$8.34	$1.04	$40.61	02/11/2018
155	Solomon Islands	OCEANIA	16	$8.37	$6.13	$10.02	19/11/2018
156	Martinique	CARIBBEAN	30	$8.46	$0.78	$33.92	13/11/2018
157	Bolivia	SOUTH AMERICA	28	$8.51	$2.08	$20.66	30/10/2018
158	Niue	OCEANIA	10	$9.20	$4.37	$28.00	15/11/2018
159	Lebanon	NEAR EAST	20	$9.21	$1.30	$20.00	12/11/2018
160	Mali	SUB-SAHARAN AFRICA	15	$9.22	$3.10	$22.75	13/11/2018
161	Taiwan	ASIA (EX. NEAR EAST)	35	$9.49	$1.03	$43.13	27/11/2018
162	Caribbean Netherlands	CARIBBEAN	34	$9.57	$2.00	$35.00	06/11/2018
163	Saint Lucia	CARIBBEAN	25	$9.78	$2.33	$22.16	12/11/2018
164	New Zealand	OCEANIA	42	$9.79	$1.91	$35.49	15/11/2018
165	China	ASIA (EX. NEAR EAST)	28	$9.89	$0.87	$26.61	07/11/2018
166	Mayotte	SUB-SAHARAN AFRICA	8	$10.18	$0.90	$33.90	09/11/2018
167	United Arab Emirates	NEAR EAST	21	$10.23	$2.17	$28.30	23/10/2018
168	Svalbard and Jan Mayen	WESTERN EUROPE	11	$10.26	$2.32	$28.89	20/11/2018
169	Saint-Martin (France)	CARIBBEAN	29	$10.40	$0.56	$24.73	30/10/2018

Table A.1 continued from previous page

Rank	Name	Continental region	Plans measured	Average price of 1GB	Cheapest 1GB	Most expensive 1GB	Sample date
170	Namibia	SUB-SAHARAN AFRICA	24	$11.02	$2.35	$26.80	14/11/2018
171	Kiribati	OCEANIA	22	$11.05	$4.30	$21.34	12/11/2018
172	Puerto Rico	CARIBBEAN	21	$11.12	$3.00	$25.00	16/11/2018
173	Oman	NEAR EAST	38	$11.28	$3.90	$25.98	15/11/2018
174	Papua New Guinea	OCEANIA	34	$11.51	$6.83	$18.36	16/11/2018
175	Grenada	CARIBBEAN	20	$11.56	$4.24	$29.60	25/10/2018
176	Antigua and Barbuda	CARIBBEAN	41	$11.71	$1.94	$61.39	24/10/2018
177	Togo	SUB-SAHARAN AFRICA	3	$11.76	$11.49	$12.31	29/10/2018
178	Saint Vincent and the Grenadines	CARIBBEAN	23	$12.00	$3.69	$37.00	05/11/2018
179	Canada	NORTHERN AMERICA	60	$12.02	$3.73	$60.37	26/10/2018
180	Swaziland	SUB-SAHARAN AFRICA	45	$12.14	$1.58	$39.00	21/11/2018
181	Belgium	WESTERN EUROPE	60	$12.30	$2.21	$101.77	29/10/2018
182	United States	NORTHERN AMERICA	32	$12.37	$1.50	$60.00	05/11/2018
183	Curaçao	CARIBBEAN	25	$12.42	$7.72	$27.64	07/11/2018
184	Comoros	SUB-SAHARAN AFRICA	10	$12.57	$2.29	$22.92	12/11/2018
185	Cuba	CARIBBEAN	5	$12.58	$11.25	$13.33	27/11/2018
186	Aruba	CARIBBEAN	22	$12.70	$7.41	$22.21	25/10/2018
187	Andorra	WESTERN EUROPE	10	$12.71	$5.83	$35.46	23/10/2018
188	Gibraltar	WESTERN EUROPE	11	$12.82	$3.21	$30.77	30/10/2018
189	Micronesia	OCEANIA	7	$12.87	$0.83	$50.00	29/10/2018
190	Guam	OCEANIA	35	$12.97	$1.74	$70.00	08/11/2018
191	Virgin Islands (U.S.)	CARIBBEAN	21	$13.10	$2.40	$59.96	22/11/2018
192	Norway	WESTERN EUROPE	49	$13.21	$1.27	$114.87	14/11/2018
193	French Guiana	SOUTH AMERICA	28	$13.41	$0.57	$112.96	08/11/2018
194	Liechtenstein	WESTERN EUROPE	17	$13.95	$3.49	$37.84	02/11/2018
195	Portugal	WESTERN EUROPE	25	$13.98	$2.12	$67.79	19/11/2018
196	Botswana	SUB-SAHARAN AFRICA	15	$14.12	$9.01	$21.34	06/11/2018
197	Dominica	CARIBBEAN	25	$14.60	$6.17	$29.60	06/11/2018

Table A.1 continued from previous page

Rank	Name	Continental region	Plans measured	Average price of 1GB	Cheapest 1GB	Most expensive 1GB	Sample date
198	Montserrat	CARIBBEAN	17	$14.61	$4.93	$33.30	13/11/2018
199	Anguilla	CARIBBEAN	23	$14.90	$1.97	$37.00	24/10/2018
200	Saint Kitts and Nevis	CARIBBEAN	31	$15.05	$5.38	$37.00	12/11/2018
201	South Korea	ASIA (EX. NEAR EAST)	15	$15.12	$0.47	$34.02	13/11/2018
202	Yemen	NEAR EAST	29	$15.73	$4.00	$39.95	22/11/2018
203	Mozambique	SUB-SAHARAN AFRICA	34	$15.82	$0.80	$55.84	13/11/2018
204	Greenland	NORTHERN AMERICA	3	$16.79	$12.60	$22.65	29/10/2018
205	New Caledonia	OCEANIA	9	$16.91	$11.26	$23.89	26/10/2018
206	Trinidad and Tobago	CARIBBEAN	7	$17.10	$9.79	$29.52	21/11/2018
207	Cook Islands	OCEANIA	8	$18.12	$11.38	$33.45	06/11/2018
208	Virgin Islands (British)	CARIBBEAN	42	$18.55	$5.83	$40.00	22/11/2018
209	Malta	WESTERN EUROPE	29	$18.79	$2.26	$90.46	30/10/2018
210	Seychelles	SUB-SAHARAN AFRICA	23	$19.55	$3.66	$71.72	19/11/2018
211	Turkmenistan	CIS (FORMER USSR)	7	$19.81	$10.01	$42.89	21/11/2018
212	Switzerland	WESTERN EUROPE	12	$20.22	$8.30	$49.79	24/10/2018
213	Cyprus	NEAR EAST	13	$20.35	$6.39	$38.44	23/10/2018
214	Benin	SUB-SAHARAN AFRICA	16	$20.99	$17.24	$24.62	23/10/2018
215	French Polynesia	OCEANIA	14	$21.64	$8.91	$49.29	16/11/2018
216	Turks and Caicos Islands	CARIBBEAN	26	$23.09	$10.00	$46.67	21/11/2018
217	Chad	SUB-SAHARAN AFRICA	10	$23.33	$9.39	$68.94	21/11/2018
218	Tonga	OCEANIA	8	$25.52	$4.43	$54.25	21/11/2018
219	Cayman Islands	CARIBBEAN	26	$26.79	$3.99	$143.69	12/11/2018
220	Wallis and Fortuna	OCEANIA	6	$26.86	$15.40	$47.40	05/11/2018
221	Nauru	OCEANIA	5	$28.23	$12.25	$38.41	15/11/2018
222	Tokelau	OCEANIA	15	$29.96	$17.06	$40.87	28/11/2018
223	Samoa	OCEANIA	42	$30.09	$1.33	$253.43	22/11/2018
224	Greece	EASTERN EUROPE	15	$32.71	$2.37	$106.85	08/11/2018
225	Bermuda	NORTHERN AMERICA	25	$37.73	$6.25	$100.01	06/11/2018

Table A.1 continued from previous page

Rank	Name	Continental region	Plans measured	Average price of 1GB	Cheapest 1GB	Most expensive 1GB	Sample date
226	Djibouti	SUB-SAHARAN AFRICA	5	$37.92	$2.81	$112.54	06/11/2018
227	Falkland Islands	SOUTH AMERICA	4	$47.39	$28.00	$77.55	26/10/2018
228	Saint Helena	SUB-SAHARAN AFRICA	4	$55.47	$51.70	$64.63	26/10/2018
229	Equatorial Guinea	SUB-SAHARAN AFRICA	12	$65.83	$27.58	$114.79	26/10/2018
230	Zimbabwe	SUB-SAHARAN AFRICA	37	$75.20	$12.50	$138.46	30/10/2018

Table A.1: Cost of 1 GB of mobile data in 230 countries. Source: (Cable.co.uk, 2019)

Appendix B

Worldwide Broadband Pricing

In Table A.1, the average prices for broadband packages in 195 countries can be seen. The study conducted by Cable.co.uk (2018) considers broadbandh packages for Dial-up, ADSL and fiber internet packages. This table divides the countries in Continental regions, and also includes the number of plans measured from different countries dated with a sample date, the monthly average price for the broadband package and the average cost per month for each megabit of speed of internet. The prices are in USD, with the exchange rate applied until 28.09.2018.

Rank	**Name**	**Continental region**	**Packages measured**	**Cheapest broadband package**	**Most expensive broadband package**	**Average monthly cost of broadband**	**Average monthly cost of broadband per MB/s**	**Sample date**
1	Ukraine	CIS (FORMER USSR)	15	$2.16	$11.10	$5.00	$0.04	03/09/2018
2	Sri Lanka	ASIA (EX. NEAR EAST)	3	$3.19	$8.79	$5.65	$0.49	18/09/2018
3	Iran	ASIA (EX. NEAR EAST)	36	$1.87	$19.03	$8.20	$2.89	24/08/2018
4	Russian Federation	CIS (FORMER USSR)	28	$4.89	$27.42	$9.77	$0.32	14/09/2018
5	Belarus	CIS (FORMER USSR)	22	$5.15	$19.92	$10.46	$0.75	10/09/2018
6	Moldova	CIS (FORMER USSR)	11	$2.90	$20.12	$11.28	$0.27	31/08/2018
7	Syria	NEAR EAST	41	$2.62	$63.05	$13.00	$4.30	12/09/2018
8	Israel	NEAR EAST	28	$5.52	$27.31	$13.02	$0.42	12/09/2018
9	Egypt	NORTHERN AFRICA	32	$2.79	$72.52	$13.58	$4.48	29/08/2018
10	Romania	EASTERN EUROPE	20	$6.97	$59.25	$14.42	$0.66	14/09/2018
11	Argentina	SOUTH AMERICA	27	$8.18	$46.09	$15.51	$1.29	11/09/2018
12	Turkey	NEAR EAST	35	$3.99	$145.53	$15.96	$0.47	13/09/2018
13	Kazakhstan	CIS (FORMER USSR)	19	$5.30	$54.60	$16.14	$11.23	21/09/2018
14	Nepal	ASIA (EX. NEAR EAST)	31	$5.70	$64.48	$16.47	$1.37	29/08/2018
15	Lithuania	BALTICS	20	$5.69	$41.94	$16.84	$0.09	11/09/2018
16	Mongolia	ASIA (EX. NEAR EAST)	23	$4.06	$67.99	$17.97	$3.87	13/09/2018
17	Poland	EASTERN EUROPE	40	$9.05	$37.80	$18.27	$0.11	12/09/2018
18	Hungary	EASTERN EUROPE	22	$6.54	$46.33	$18.37	$0.25	29/08/2018
19	Latvia	BALTICS	18	$7.43	$30.39	$18.68	$0.31	03/09/2018
20	Georgia	CIS (FORMER USSR)	25	$8.84	$41.33	$18.70	$2.06	15/08/2018
21	Serbia	EASTERN EUROPE	21	$8.80	$41.22	$19.24	$1.09	21/09/2018
22	Venezuela	SOUTH AMERICA	10	$1.68	$51.17	$20.03	$7.64	20/09/2018
23	Uzbekistan	CIS (FORMER USSR)	33	$3.69	$77.96	$21.26	$4.56	14/09/2018
24	Slovakia	EASTERN EUROPE	32	$8.42	$51.47	$21.62	$0.88	14/09/2018
25	Yemen	NEAR EAST	5	$8.99	$44.95	$22.17	$20.24	24/08/2018
26	Saint Martin (France)	CARIBBEAN	5	$21.21	$29.94	$23.78	$3.08	29/08/2018
27	Tunisia	NORTHERN AFRICA	38	$4.46	$81.14	$24.28	$1.52	12/09/2018

Table B.1 continued from previous page

Rank	Name	Continental region	Packages measured	Cheapest broadband package	Most expensive broadband package	Average monthly cost of broadband	Average monthly cost of broadband per MB/s	Sample date
28	Pakistan	ASIA (EX. NEAR EAST)	33	$6.98	$56.58	$24.87	$3.03	29/08/2018
29	Thailand	ASIA (EX. NEAR EAST)	19	$13.92	$40.20	$25.58	$0.33	20/09/2018
30	Czech Republic	EASTERN EUROPE	16	$18.05	$42.40	$25.94	$0.57	17/09/2018
31	Taiwan	ASIA (EX. NEAR EAST)	41	$3.57	$72.09	$26.39	$0.92	14/09/2018
32	Croatia	EASTERN EUROPE	23	$17.95	$40.61	$26.74	$1.02	03/09/2018
33	Estonia	BALTICS	5	$17.41	$38.32	$27.63	$0.50	19/09/2018
34	India	ASIA (EX. NEAR EAST)	34	$5.80	$234.81	$28.23	$0.60	03/09/2018
35	Tajikistan	CIS (FORMER USSR)	16	$3.27	$74.06	$29.16	$34.68	19/09/2018
36	Italy	WESTERN EUROPE	20	$5.06	$58.65	$29.48	$3.52	29/08/2018
37	Macedonia	EASTERN EUROPE	18	$7.46	$82.40	$29.50	$0.87	14/09/2018
38	Dominican Republic	CARIBBEAN	18	$14.94	$57.66	$29.66	$15.46	29/08/2018
39	Bulgaria	EASTERN EUROPE	17	$7.12	$90.13	$30.27	$0.19	06/09/2018
40	France	WESTERN EUROPE	16	$10.55	$54.01	$31.14	$0.54	17/09/2018
41	Slovenia	EASTERN EUROPE	13	$15.09	$49.94	$31.72	$2.01	14/09/2018
42	Palestine, State of	NEAR EAST	16	$7.72	$82.76	$31.79	$1.76	20/09/2018
43	South Korea	ASIA (EX. NEAR EAST)	18	$14.88	$46.97	$32.29	$0.21	24/08/2018
44	Albania	EASTERN EUROPE	21	$14.62	$114.42	$33.17	$1.35	06/09/2018
45	Mexico	CENTRAL AMERICA	28	$11.53	$82.43	$33.32	$1.61	13/09/2018
46	Algeria	NORTHERN AFRICA	5	$13.54	$66.85	$33.51	$7.57	22/08/2018
47	Montenegro	EASTERN EUROPE	12	$20.89	$69.67	$33.87	$1.17	17/09/2018
48	Réunion	SUB-SAHARAN AFRICA	6	$17.42	$51.08	$35.45	$0.34	20/09/2018
49	Bosnia and Herzegovina	EASTERN EUROPE	40	$7.72	$140.16	$35.47	$3.44	05/09/2018
50	Sudan	SUB-SAHARAN AFRICA	10	$5.52	$91.02	$35.86	$11.13	20/09/2018
51	Bangladesh	ASIA (EX. NEAR EAST)	25	$12.81	$97.06	$36.33	$5.86	06/09/2018
52	Saint Barthélemy	CARIBBEAN	6	$23.22	$48.66	$36.62	$3.10	03/09/2018
53	Germany	WESTERN EUROPE	38	$13.53	$232.27	$36.68	$0.67	07/09/2018

Table B.1 continued from previous page

Rank	Name	Continental region	Packages measured	Cheapest broadband package	Most expensive broadband package	Average monthly cost of broadband	Average monthly cost of broadband per MB/s	Sample date
54	Azerbaijan	CIS (FORMER USSR)	41	$6.12	$222.66	$36.97	$8.11	04/09/2018
55	Monaco	WESTERN EUROPE	5	$23.22	$64.25	$37.00	$0.17	18/09/2018
56	Japan	ASIA (EX. NEAR EAST)	35	$6.87	$74.68	$37.15	$1.81	21/09/2018
57	Myanmar	ASIA (EX. NEAR EAST)	22	$6.84	$118.06	$37.56	$10.00	11/09/2018
58	Lebanon	NEAR EAST	26	$10.19	$81.84	$37.60	$18.29	11/09/2018
59	French Guiana	SOUTH AMERICA	5	$28.92	$46.05	$39.15	$3.78	19/09/2018
60	El Salvador	CENTRAL AMERICA	11	$25.00	$70.00	$39.32	$4.49	20/09/2018
61	United Kingdom	WESTERN EUROPE	36	$22.21	$67.49	$39.58	$1.19	29/08/2018
62	Guatemala	CENTRAL AMERICA	12	$19.20	$125.65	$41.27	$12.21	30/08/2018
63	China	ASIA (EX. NEAR EAST)	23	$4.36	$366.72	$41.29	$0.42	10/09/2018
64	Spain	WESTERN EUROPE	22	$15.10	$65.04	$42.38	$0.66	07/09/2018
65	Mayotte	SUB-SAHARAN AFRICA	6	$20.79	$60.86	$43.16	$11.12	20/09/2018
66	Martinique	CARIBBEAN	6	$33.57	$48.66	$43.50	$3.56	03/09/2018
67	Macau	ASIA (EX. NEAR EAST)	9	$16.00	$80.82	$43.72	$1.62	31/08/2018
68	Colombia	SOUTH AMERICA	21	$22.44	$131.81	$44.81	$2.02	10/09/2018
69	Chile	SOUTH AMERICA	26	$22.72	$78.03	$45.50	$0.53	10/09/2018
70	Belgium	WESTERN EUROPE	25	$21.20	$69.69	$45.68	$0.86	28/08/2018
71	Peru	SOUTH AMERICA	20	$14.86	$136.41	$45.94	$2.76	20/09/2018
72	Sint Maarten	CARIBBEAN	9	$27.99	$58.77	$46.08	$7.74	20/09/2018
73	Uruguay	SOUTH AMERICA	22	$13.46	$80.79	$46.50	$3.78	03/09/2018
74	Armenia	CIS (FORMER USSR)	41	$4.95	$222.93	$46.79	$6.59	05/09/2018
75	Bolivia	CENTRAL AMERICA	36	$12.80	$119.20	$47.83	$9.19	06/09/2018
76	Malaysia	ASIA (EX. NEAR EAST)	27	$20.75	$117.47	$47.92	$3.06	15/08/2018
77	Brazil	SOUTH AMERICA	33	$8.20	$388.71	$48.00	$2.18	07/09/2018
78	Singapore	ASIA (EX. NEAR EAST)	8	$21.87	$141.49	$50.43	$0.03	29/08/2018
79	Austria	WESTERN EUROPE	22	$26.77	$99.94	$50.70	$0.77	04/09/2018

Table B.1 continued from previous page

Rank	Name	Continental region	Packages measured	Cheapest broadband package	Most expensive broadband package	Average monthly cost of broadband	Average monthly cost of broadband per MB/s	Sample date
80	Denmark	WESTERN EUROPE	18	$35.67	$112.75	$51.11	$0.83	11/09/2018
81	Iraq	NEAR EAST	7	$32.47	$99.90	$51.95	$1.90	21/08/2018
82	Finland	WESTERN EUROPE	7	$34.73	$92.80	$52.23	$0.41	17/09/2018
83	Morocco	NORTHERN AFRICA	11	$26.43	$123.85	$52.74	$2.27	18/09/2018
84	Australia	OCEANIA	27	$25.26	$86.94	$52.77	$1.80	05/09/2018
85	Afghanistan	ASIA (EX. NEAR EAST)	20	$3.92	$418.49	$52.78	$34.68	15/08/2018
86	Andorra	WESTERN EUROPE	4	$18.82	$84.35	$52.80	$4.86	17/08/2018
87	Cyprus	NEAR EAST	19	$22.08	$112.38	$53.01	$2.87	10/09/2018
88	Philippines	ASIA (EX. NEAR EAST)	28	$18.03	$175.77	$53.14	$3.29	14/09/2018
89	Malta	WESTERN EUROPE	12	$26.71	$118.56	$53.70	$0.91	18/09/2018
90	Gibraltar	WESTERN EUROPE	9	$26.32	$88.05	$54.07	$0.90	21/08/2018
91	Kuwait	NEAR EAST	40	$9.34	$147.57	$54.60	$4.76	24/08/2018
92	Indonesia	ASIA (EX. NEAR EAST)	22	$15.44	$335.57	$54.85	$0.91	24/08/2018
93	South Africa	SUB-SAHARAN AFRICA	36	$6.99	$126.37	$55.25	$3.49	14/09/2018
94	Sweden	WESTERN EUROPE	12	$26.65	$105.57	$55.99	$0.40	19/09/2018
95	San Marino	WESTERN EUROPE	7	$24.08	$97.56	$56.17	$0.51	20/09/2018
96	Falkland Islands	SOUTH AMERICA	3	$21.77	$100.15	$57.48	$24.02	19/09/2018
97	Canada	NORTHERN AMERICA	28	$23.04	$121.68	$57.66	$2.03	31/08/2018
98	Greece	WESTERN EUROPE	18	$18.29	$247.77	$58.22	$0.86	23/08/2018
99	Jersey	WESTERN EUROPE	7	$24.81	$94.70	$58.22	$0.12	19/09/2018
100	Belize	CENTRAL AMERICA	3	$37.17	$86.58	$58.58	$5.65	20/09/2018
101	Cameroon	SUB-SAHARAN AFRICA	6	$28.64	$98.75	$58.75	$43.97	23/08/2018
102	New Zealand	OCEANIA	36	$42.35	$88.73	$58.77	$0.55	13/09/2018
103	The Netherlands	WESTERN EUROPE	22	$29.04	$98.66	$59.23	$0.83	14/09/2018
104	Guadeloupe	CARIBBEAN	6	$40.64	$116.03	$60.23	$2.49	19/09/2018
105	Grenada	CARIBBEAN	8	$25.25	$132.59	$60.37	$2.67	15/08/2018

Table B.1 continued from previous page

Rank	Name	Continental region	Packages measured	Cheapest broadband package	Most expensive broadband package	Average monthly cost of broadband	Average monthly cost of broadband per MB/s	Sample date
106	Trinidad and Tobago	CARIBBEAN	19	$21.38	$103.12	$60.77	$3.33	30/08/2018
107	Portugal	WESTERN EUROPE	12	$31.06	$109.36	$61.15	$0.71	19/09/2018
108	Cambodia	ASIA (EX. NEAR EAST)	34	$15.99	$353.33	$62.29	$19.41	20/09/2019
109	Ecuador	CENTRAL AMERICA	32	$23.51	$224.00	$62.45	$2.61	07/09/2018
110	Jamaica	CARIBBEAN	12	$24.75	$132.61	$62.57	$4.89	21/08/2018
111	Guernsey	WESTERN EUROPE	6	$49.63	$77.61	$62.68	$1.79	15/08/2018
112	Puerto Rico	CARIBBEAN	29	$18.99	$194.99	$63.45	$7.87	14/09/2018
113	Nicaragua	CENTRAL AMERICA	13	$27.99	$125.00	$63.84	$9.97	18/09/2018
114	Mauritius	SUB-SAHARAN AFRICA	4	$29.05	$122.58	$64.06	$2.09	19/09/2018
115	Fiji	OCEANIA	9	$16.43	$151.66	$64.49	$66.89	19/09/2018
116	Ireland	WESTERN EUROPE	18	$37.55	$88.05	$65.12	$0.40	31/08/2018
117	Åland Islands	WESTERN EUROPE	20	$15.10	$569.10	$65.28	$2.00	06/09/2018
118	Madagascar	SUB-SAHARAN AFRICA	3	$57.08	$71.42	$66.64	$1.43	19/09/2018
119	United States	NORTHERN AMERICA	25	$20.00	$199.95	$67.69	$1.26	13/09/2018
120	Isle of Man	WESTERN EUROPE	24	$24.49	$190.73	$68.07	$0.93	04/09/2018
121	Honduras	CENTRAL AMERICA	12	$27.00	$129.00	$68.50	$7.28	23/08/2018
122	Swaziland	SUB-SAHARAN AFRICA	9	$5.98	$278.83	$68.78	$52.46	20/09/2018
123	Mozambique	SUB-SAHARAN AFRICA	12	$13.50	$127.42	$69.11	$20.19	23/08/2018
124	Vietnam	ASIA (EX. NEAR EAST)	17	$10.74	$275.94	$69.63	$2.67	20/09/2018
125	Liechtenstein	WESTERN EUROPE	19	$35.81	$115.00	$70.52	$2.38	11/09/2018
126	Saint Lucia	CARIBBEAN	5	$32.94	$124.88	$71.02	$5.32	19/09/2018
127	Luxembourg	WESTERN EUROPE	34	$27.94	$182.80	$71.15	$1.06	04/09/2018
128	Dominica	CARIBBEAN	3	$32.17	$110.21	$71.43	$15.95	19/09/2018
129	Hong Kong	ASIA (EX. NEAR EAST)	14	$24.03	$383.55	$72.68	$0.40	29/08/2018
130	Bahamas	CARIBBEAN	13	$29.77	$209.31	$72.77	$5.74	06/09/2018
131	Costa Rica	CENTRAL AMERICA	30	$20.55	$356.61	$73.51	$3.65	07/09/2018

Table B.1 continued from previous page

Rank	Name	Continental region	Packages measured	Cheapest broadband package	Most expensive broadband package	Average monthly cost of broadband	Average monthly cost of broadband per MB/s	Sample date
132	Côte d'Ivoire	SUB-SAHARAN AFRICA	14	$15.97	$140.15	$73.87	$12.88	23/08/2018
133	Norway	WESTERN EUROPE	34	$36.61	$182.45	$73.92	$2.50	13/09/2018
134	St. Pierre and Miquelon	CARIBBEAN	6	$26.62	$226.48	$74.22	$10.90	20/09/2018
135	Saint Kitts and Nevis	CARIBBEAN	12	$32.36	$185.01	$74.71	$5.84	03/09/2018
136	Kenya	SUB-SAHARAN AFRICA	19	$24.77	$198.28	$75.18	$2.42	22/08/2018
137	Montserrat	CARIBBEAN	6	$40.30	$129.14	$76.09	$20.65	19/09/2018
138	Turkmenistan	CIS (FORMER USSR)	8	$54.18	$100.27	$76.15	$117.73	20/09/2018
139	Iceland	WESTERN EUROPE	15	$39.52	$112.60	$76.66	$0.63	24/09/2018
140	Jordan	NEAR EAST	26	$25.36	$211.36	$77.45	$1.21	04/09/2018
141	New Caledonia	OCEANIA	13	$10.24	$307.35	$77.71	$3.99	14/09/2018
142	Faroe Islands	WESTERN EUROPE	14	$72.32	$87.35	$78.58	$1.58	14/09/2018
143	Switzerland	WESTERN EUROPE	33	$27.19	$161.80	$80.00	$3.02	31/08/2018
144	Curaçao	CARIBBEAN	15	$34.90	$183.92	$80.23	$2.84	20/09/2018
145	Saint Helena	SUB-SAHARAN AFRICA	6	$19.02	$204.57	$80.26	$46.37	23/08/2018
146	Maldives	ASIA (EX. NEAR EAST)	16	$22.72	$156.74	$81.55	$4.51	14/09/2018
147	Angola	SUB-SAHARAN AFRICA	15	$22.57	$192.06	$82.43	$13.14	11/09/2018
148	Benin	SUB-SAHARAN AFRICA	5	$37.40	$144.88	$83.94	$77.45	21/08/2018
149	Nigeria	SUB-SAHARAN AFRICA	13	$33.88	$175.07	$84.16	$7.17	19/09/2018
150	French Polynesia	OCEANIA	6	$39.52	$145.38	$85.63	$28.62	19/09/2018
151	Virgin Islands (U.S.)	CARIBBEAN	8	$51.84	$151.84	$88.01	$5.32	22/08/2018
152	Guam	OCEANIA	3	$79.71	$99.71	$89.71	$3.63	24/08/2018
153	Botswana	SUB-SAHARAN AFRICA	14	$19.51	$235.54	$91.64	$25.14	07/09/2018
154	Saudi Arabia	NEAR EAST	12	$21.33	$223.63	$95.72	$2.16	30/08/2018
155	Bahrain	NEAR EAST	25	$21.22	$398.98	$96.29	$6.79	05/09/2018
156	Djibouti	SUB-SAHARAN AFRICA	4	$55.26	$145.18	$97.41	$21.16	22/08/2018
157	Marshall Islands	OCEANIA	4	$54.11	$151.61	$97.45	$149.77	19/09/2018

Table B.1 continued from previous page

Rank	**Name**	**Continental region**	**Packages measured**	**Cheapest broadband package**	**Most expensive broadband package**	**Average monthly cost of broadband**	**Average monthly cost of broadband per MB/s**	**Sample date**
158	Anguilla	CARIBBEAN	11	$27.75	$203.14	$100.07	$4.75	07/09/2018
159	Gabon	SUB-SAHARAN AFRICA	8	$32.52	$273.79	$103.59	$19.63	15/08/2018
160	Micronesia	OCEANIA	5	$26.00	$226.00	$103.60	$35.32	29/08/2018
161	American Samoa	OCEANIA	10	$49.95	$173.49	$103.69	$88.59	04/09/2018
162	Kyrgyzstan	CIS (FORMER USSR)	24	$1.27	$432.87	$108.22	$29.48	14/09/2018
163	Panama	CENTRAL AMERICA	8	$20.01	$263.25	$108.38	$0.40	19/09/2018
164	Lesotho	SUB-SAHARAN AFRICA	4	$38.75	$207.83	$108.49	$63.98	29/08/2018
165	Caribbean Netherlands	CARIBBEAN	3	$86.80	$136.95	$110.12	$11.62	19/09/2018
166	Barbados	CARIBBEAN	10	$39.69	$302.60	$111.86	$0.49	10/09/2018
167	Comoros	SUB-SAHARAN AFRICA	4	$37.55	$209.50	$114.34	$68.34	21/08/2018
168	Somalia	SUB-SAHARAN AFRICA	5	$7.50	$300.00	$117.50	$250.43	22/08/2018
169	Niger	SUB-SAHARAN AFRICA	5	$29.57	$281.18	$118.80	$263.15	23/08/2018
170	Turks and Caicos Islands	CARIBBEAN	9	$69.00	$209.99	$119.21	$5.41	20/09/2018
171	Seychelles	SUB-SAHARAN AFRICA	5	$36.38	$275.62	$122.73	$65.97	20/09/2018
172	Guyana	CARIBBEAN	12	$43.36	$406.46	$123.11	$40.09	23/08/2018
173	Brunei Darussalam	ASIA (EX. NEAR EAST)	8	$27.42	$265.05	$123.29	$2.52	10/09/2018
174	Greenland	NORTHERN AMERICA	6	$50.46	$186.75	$123.80	$33.62	11/09/2018
175	Bermuda	NORTHERN AMERICA	41	$30.00	$339.00	$124.36	$13.04	10/09/2018
176	Ethiopia	SUB-SAHARAN AFRICA	9	$21.29	$265.30	$125.19	$31.39	29/08/2018
177	Zimbabwe	SUB-SAHARAN AFRICA	7	$15.00	$339.00	$128.71	$6.89	19/09/2018
178	Sierra Leone	SUB-SAHARAN AFRICA	3	$66.01	$222.79	$135.62	$60.24	20/09/2018
179	Vanuatu	OCEANIA	10	$47.76	$324.53	$138.54	$74.73	19/09/2018
180	Qatar	NEAR EAST	14	$54.93	$528.70	$140.58	$14.05	24/08/2018
181	Virgin Islands (British)	CARIBBEAN	4	$81.58	$209.92	$141.17	$4.52	22/08/2018
182	Oman	NEAR EAST	13	$54.12	$592.26	$150.63	$3.94	30/08/2018
183	United Arab Emirates	NEAR EAST	7	$23.40	$439.85	$157.10	$16.50	15/08/2018

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Rank	Name	Continental region	Packages measured	Cheapest broadband package	Most expensive broadband package	Average monthly cost of broadband	Average monthly cost of broadband per MB/s	Sample date
184	Cayman Islands	CARIBBEAN	11	$82.31	$256.85	$158.69	$6.33	31/08/2018
185	Mali	SUB-SAHARAN AFRICA	7	$19.77	$498.92	$160.53	$48.45	21/08/2018
186	Cook Islands	OCEANIA	4	$20.65	$466.10	$171.34	$20.47	10/09/2018
187	Antigua and Barbuda	CARIBBEAN	8	$48.10	$368.17	$177.15	$4.79	30/08/2018
188	Tanzania	SUB-SAHARAN AFRICA	13	$30.14	$436.87	$181.80	$52.33	19/09/2018
189	Burkina Faso	SUB-SAHARAN AFRICA	6	$23.92	$651.72	$201.94	$39.45	22/08/2018
190	Haiti	CARIBBEAN	9	$54.54	$399.00	$207.39	$10.53	03/09/2018
191	Paraguay	SOUTH AMERICA	33	$23.42	$567.96	$210.83	$20.16	19/09/2018
192	Lao	ASIA (EX. NEAR EAST)	39	$16.36	$818.23	$239.25	$13.91	31/08/2018
193	Namibia	SUB-SAHARAN AFRICA	13	$71.68	$1 117.87	$383.83	$17.79	18/09/2018
194	Papua New Guinea	OCEANIA	18	$6.28	$1 849.09	$571.67	$81.25	19/09/2018
195	Mauritania	SUB-SAHARAN AFRICA	4	$307.26	$1 368.72	$768.16	$127.15	19/09/2018

Table B.1: Broadband prices worldwide in USD. Source: Cable.co.uk (2018)