Leading-edge 5G Research and Innovation: An undivided commitment of Europe[1]

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Abstract Research and Innovation paving the way towards the development of 5G Communication Networks has been subject of huge support and political commitment from Europe, especially under the Horizon 2020 programme. The European Commission has notably implemented with industry the 5G Public Private Partnership as an R&I vehicle to structure and foster European research in this domain and also to further support the deployment agenda set out in the 5G Action Plan. This paper reviews the main development and impacts of the 5G PPP R&I actions and outlines future actions.

[1] NB: The views expressed in this article are those of the authors and shall not be considered as official statements of the European Commission.

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1 Introduction

Early reflection about the evolution of mobile communication networks "beyond 4G" started soon after the first deployment of a 4G commercial network in Sweden, in 2010. In those days, it was already apparent that the very fast growth of mobile traffic, between 50 to 100% increase on a yearly basis, as well as the prospects to serve innovative Internet of Things (IoT) applications would drive further R&D in the mobile communication domain.

Taking note of these developments, the European Commission initiated visionary EU-funded research activities already in 2012[i]. At the Mobile World Congress in 2013, Commissioner Kroes challenged the industry to come up with a structuring European approach for leading edge R&D in 5G network technologies and systems. This eventually led to the setup of the European 5G Public Private Partnership (5G PPP). The 5G PPP is implemented under the European Horizon 2020 programme with about € 700 Million of public support over the 2014-2020 period. The private sector contribution is matching that amount by a factor of at least five. Altogether, this represents the largest 5G R&D initiative in the world.

Piggybacking on these intense technological efforts, and taking stock of fast international developments, Commissioner Oettinger made a formal call to the European industry at the Mobile World Congress in 2016 in view of developing an ambitious 5G deployment roadmap for Europe. Industry responded with a 5G manifesto[ii] and the Commission adopted the 5G Action Plan (5G AP) on 14 September 2016[iii] as part of a comprehensive connectivity package setting out the European ambitions for a Gigabit Society.

These initiatives materialise the importance of 5G networks for Europe. They are considered by the European Commission as a strategic asset for the digital society and to support the digital transformation of the industry and the public sector.

2 5G Vision driving R&D and technological requirements

There are multiple socio-economic developments driving the telecom and the wider ICT sector. Broadband access has become the norm and the advent of ever more feature rich content located in remote clouds coupled with ever more powerful end user devices like tablets and smartphones call for networks of ever-higher capacity and speeds. Bandwidth consumption of mobile networks, even if one order of magnitude lower than on fixed networks, continue to grow at a rate of at least 50% in most countries, mainly due to video traffic. The advent of novel bandwidth hungry Virtual or Augmented reality (VR/AR) mobile applications will further exacerbate this trend. In addition, the advent of the Internet of things (IoT), with massive deployment of connected objects in cities or in dense location areas calls for new approaches to efficiently address huge collections of devices with minimum power consumption and efficient connectivity. Finally, the advent of new mission critical applications where response time is of the essence, such as in factories environments, healthcare, public protection or automated driving calls for extremely low latency systems with very high availability and reliability characteristics, beyond what 4G is capable of delivering. In fact, 4G design drivers were mainly based on mass-market access to high speed mobile Internet, whilst 5G also takes into account applications in professional environments requiring much higher performance and grade of service levels.

These novel requirements for future 5G networks were further refined by industry in several documents[iv], notably at ITU level. They cover: i) the "enhanced Mobile Broadband" (eMBB) scenario targeting carrier data rates larger than 10 Gb/s; ii) the massive Machine to Machine communication scenario (mMTC) targeting connectivity of millions of devices per km^2; iii) the Ultra Reliable Low Latency Communications (URLLC) scenarios, targeting latencies in the order of 1ms at the level of the User Plane. The main resulting radio requirements as worked out at ITU level are outlined in the table below[v].

	IMT-ADVANCED	IMT-2020 (5G)
PEAK DATA RATE	DL: 1 Gbps UL: 0,05 Gbps	DL: 20 Gbps UL: 10 Gbps
USER EXPERIENCED RATE	10 Mbps	100 Mbps

PEAK SPECTRAL EFFICIENCY	**DL: 15 bps/Hz** **UL: 6,75 bps/Hz**	**DL: 30 bps/Hz** **UL: 15 bps/Hz**
MOBILITY	**350 km/h**	**500 km/h**
USER PLANE LATENCY	**>10 ms**	**1 ms**
CONNECTION DENSITY	**x1000 devices/km²**	**1 million devices/km²**
NETWORK ENERGY EFFICIENCY	**1 – Normalised**	**x100 over IMT-Advanced**
AREA TRAFFIC CAPACITY	**0,1 Mbps/m²**	**10 Mbps/m² (hot spots)**
BANDWIDTH	**UP TO 20 MHz/channel**	**Up to 1 GHz/channel**

Table 1: 5G main radio KPI's

Based on this early vision, the 5G PPP developed further an "EU vision for 5G", where vertical use cases are key drivers for 5G developments. This was outlined in a White Paper[vi] released at the Mobile World Congress 2016. It describes a European approach with 5G called upon to implement a more holistic and radical network transformation to serve vertical industries, with connectivity solutions tailored "ad-hoc" to the specific digital business case of diverse industries (e.g. automotive, health care, smart factories, energy, media). This vision takes advantage of the introduction of technologies inspired from the IT/cloud computing domains such as Network Function Virtualisation (NFV) and Software Defined Networks (SDN) notably used to realise network slices over multiple domains and tailored ad-hoc to the various application requirements of multiple tenants. In this approach, the role of connectivity also shifts from a "cost factor" to an intrinsic asset of a full digital product or service. This strategy relies on the development of cross sectors ecosystems, beyond the provision of shorter-term super high rate access. It is directly in line with the wider policy ambitions of "Digitisation of the European Industry"[vii] (DEI) as presented by the Commission in April 2016.

Connected and Automated Mobility (CAM) as a lead "5G vertical"

In the context of 5G serving a multiplicity of vertical sectors, the deployment of 5G infrastructure along main transport paths in Europe by 2025 is one of the three strategic connectivity objectives set out by the Commission in its 5G Action Plan. The expectation is that 5G connectivity will be a major enabler for Connected and Automated Mobility, a key opportunity for Europe to lead in digital innovation.

All along the main pan-European transport paths, vehicles should be able to move across borders with uninterrupted 5G connectivity and guaranteed quality of service level to ensure business continuity for CAM applications, i.e. while changing operational, regulatory and administrative environments.

Against this background, the Commission is encouraging cooperation between Member States on cross-border initiatives for the establishment of large scale testing and early deployment of 5G corridors, including on aspects related to the cross-border exchange of road safety and traffic information, data access, data quality and liability.

In 2017 and 2018, several Member States and EEA (European Economic Area) countries signed Letters of Intent (LoI) to establish 5G cross-border corridors for large scale testing and early deployment purpose. Corridors typically cover segments of motorways of at least two different neighbour Member States allowing for uninterrupted large-scale cross-border experimentation or early use of 5G for CAM.

At this stage, ten such corridors are available across neighbouring Member States, as outlined in the table below. These corridors are open for implementation of pilot experimentations of cross border CAM systems and services using the most advanced 5G technological capabilities.

Metz-Merzig-Luxembourg: FR-DE-LU
Rotterdam-Antwerpen-Eindhoven: NL-BE
Porto-Vigo, Evora-Merida: PT-ES
E8 "Aurora Borealis": NO-FI
Nordic Way2: NO-SE-FI-DK
Brenner Corridor: IT-AT-DE

Thessaloniki, Sofia-Belgrade: EL-BG-RS
EE-LV-LT Via Baltica (E67) Tallinn (EE) – Riga (LV) – Kaunas (LT) – Lithuanian/Polish border
LT-PL Via Baltica Kaunas-Warsaw
Greece-Turkey (8 km segment across the border)

Table 2: List of currently available 5G cross border corridors

3 Economic Opportunities

From a market perspective, 5G revenues may reach US$250 billion in 2025 with North America, Asia-Pacific, and Western Europe being the top markets[viii], of which critical and massive Machine-to-Machine communications will potentially generate significant revenues in addition to enhanced Mobile Broadband services. A study carried out for the European Commission[ix] indicates that the full benefits of the future 5G capabilities in Europe over 4 industrial sectors (automotive, healthcare, transport, utilities) may reach €113 billion per annum on the long run. In the year 2025, € 62.5 billion could already arise from the first order benefits in these four key industrial sectors. The same study also concludes that 5G introduction in Europe has the potential to generate 2 million jobs.

Other studies[x] led with a global perspective indicate that 5G penetration in 8 different industrial sectors would generate a 34% growth of the connectivity business in 2026, adding more than € 500 billion globally to the classical broadband revenues whose growth is expected to be much smaller.

Lead industry actors also predict that 5G will already represent more than 550 million connections in 2022[xi] globally, more than the current 150 million LTE subscriptions in Europe.

Altogether, the market prospects offer significant economic opportunities whilst expected saving and efficiency gains in vertical industries will also contribute to societal goals such as decreased environmental footprint or decreased number of road fatalities.

4 Technologies to realise the 5G vision

The implementation of the EU vision of 5G set out by the 5G PPP addresses a wide range of technologies. The Commission has recognised the need to move towards the "Gigabit society"[xii]. Meeting this objective can be greatly facilitated by the increased use of wireless technologies such as in the context of 5G, taking as a target the ITU objectives[xiii] of moving beyond 10 Gb/s on the radio access. Today, the maximum throughput envisaged with LTE-A-PRO is in the order of 3.2 Gb/s, with carrier aggregation across several bands. Carrier aggregation has eventually some limitations, considering the growing complexity of devices integrating several bands and the fact that multi-band combinations may come at a loss of 20% or so of spectrum efficiency. This has prompted industry to consider the use of higher frequency bands at millimetre-wave frequency ranges, where large chunks of contiguous spectrum are available. Over the last few years, several industrial trials have demonstrated the transmission capability of higher frequency bands, (e.g. 15, 28, 73 GHz) to support data rates above 10 Gb/s, either in fixed or mobility conditions.

Still, the actual delivery of 5G capabilities requires going much beyond the availability of a new high-speed radio interface. Multiple technologies are called upon to achieve at least:

- a flexible radio access network that allows operators to manage an heterogeneous set of access technologies and to optimise the access according to the required service needs and to manage multiple radio accesses as a seamless access continuum across multiple frequency bands ranging from UHF to millimetre waves. This is needed to address the wide range of application requirements targeted by 5G, taking into account that different radio accesses at different frequency bands exhibit different coverage, bandwidth and grade of service characteristics;

- a large range of deployment scenarios, including a variety of static or moving nodes, with much denser deployment of access points, integrated backhaul/fronthaul operations, and optimised locations of Centralised Units (CU) and Distributed Units (DU) in the context of Cloud-RAN (C-RAN) implementations;

- very low latency services, with optimisation at several levels, e.g. at air interface level with MAC design enabling fast access and low Transmission Time Interval (TTI), and at architectural level using Mobile Edge Computing and in network caching techniques;

- massive connectivity services, with redesign of access protocols enabling to drastically reduce the signalling load over the air interface, whose overhead tend to grow very fast as large amounts of devices with small bursty traffic try to access a resource pool;

- high performance in high mobility scenarios, with control of Doppler effects at higher frequency ranges, use of MIMO techniques and optimisation of handover overhead in high density deployments.

The above issues may be considered as a non-exhaustive list of issues driving the industrial research agenda globally. A White Paper, presented by the 5G PPP in the context of the Mobile World Congress 2017[xiv] details the contribution of European R&D to these important issues.

Beyond these aspects, mostly related to Radio Access Network (RAN) architectures and technologies, the full transformative value of 5G requires the adoption of NFV and SDN technologies on a large scale to support a redesigned core network. This will be necessary to make 5G a truly holistic orchestration platform that integrates networking, computing and storage resources into one programmable and unified infrastructure. It embodies the vision of a flexible multi-tenant architecture where computing resources are distributed within the network including operational sites of the vertical industry stakeholders, within the base stations, in edge clouds at central offices, in regional and central clouds, and managed by different stakeholders.

The full realisation of 5G hence calls for a "next generation" Core Network architecture, based on SDN/NFV paradigms, to address an Access Agnostic Converged Core Network, enabling next generation services regardless of access network and integrating next generation devices. It feature fully flexible, programmable separate Control and Data planes, unified connectivity, security, mobility and routing management, as well unified physical infrastructure and corresponding abstractions (virtual resources, functions, etc.) control and orchestration.

Eventually a Network Operating System may be called upon to manage and orchestrate a unified access to computing, storage, memory and networking resources across wired networks, wireless (cellular and satellite, access and fronthaul/backhaul) networks. This requires the identification of abstractions of primitives, functions and corresponding states, in the control and data planes for a unified connection, security, mobility and routing management. These aspects are currently subject of intensive research work worldwide. The 5G PPP has released an Architecture White Paper addressing these issues[xv]

5 The 5G Public Private Partnership (5G PPP)

The implementation of Research and Innovation actions under the 5G PPP has been driven by a 5G roadmap[xvi] developed in 2013 and forming the basis of the contractual agreement signed between the European Commission and the private side, represented by the 5G Industrial Association (5G-IA). The 5G-IA currently include 52 members[xvii], from industry, research centres, academic institutions and user companies. SME's are also well represented, as one of the objective of the 5G PPP is to involve at least 20% of SME's as beneficiaries of the funded actions.
The definition of the R&I agenda as well as the updates of the roadmap are managed by the 5G-IA and supported by the NetWorld2020 European Technology Platform[xviii] (ETP) a body representing more than 1000 research organisations in Europe. This ensures an inclusive, open and transparent process. The 5G PPP roadmap has been defined with three phases of collaborative research:

- **Phase 1** addressing fundamental research on key technologies and architectures needed to support the 5G Vision.

- **Phase 2** addresses integration of core technologies towards the development of Prof of Concepts (PoC's), prototypes and trial involving technology validation in the context of a multiplicity of vertical use cases;
- **Phase 3** moves forward European trials and pilots, by providing a pan European end-to-end 5G experimental platform supporting the implementation of vertical large-scale trials in a multiplicity of sector. In that context, CAM receives particular attention. Phase 3 directly supports the deployment objectives set out in the 5G Action Plan.

At this stage, 49 projects have been implemented under the 5G PPP. They include 433 different organisation and include thousands of researchers and developers across Europe which have been working on innovative solutions for the definition and use of 5G. The distribution of efforts in from the participating nations is illustrated in the figure below.

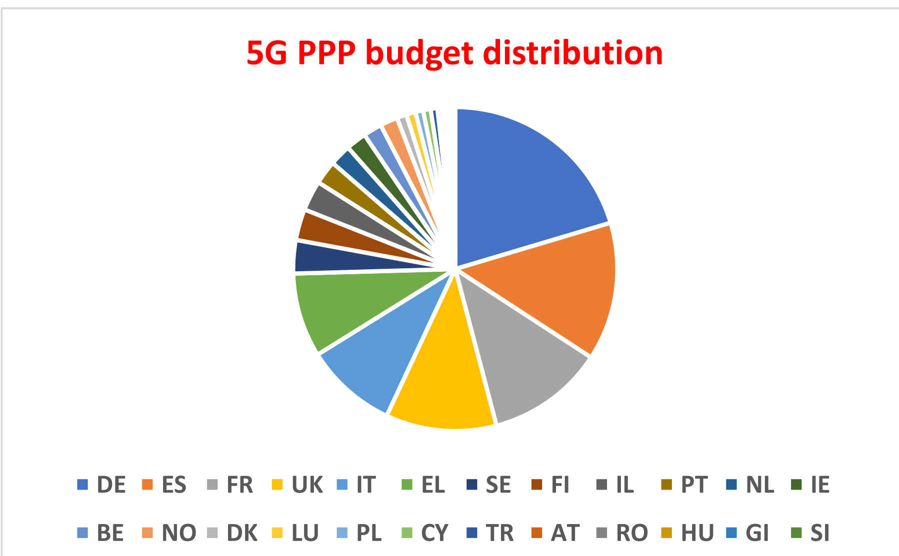

Figure 1.

Contrary to classical R&I implementation, contracted projects do not run in isolation. A key part of the 5G PPP structure is a set of cross-projects and cross-initiative working groups. The working groups are the means to establish and publish program level positions on issues that impact global 5G developments or may be the basis for liaison or interaction with external bodies such as other regions or standards bodies. Main deliverables of this joint work include:

- 5G PPP 5G Architecture White Paper Revision 2.0[xix] (December 2017)
  Highlighting the key 5G architecture design recommendations from 5G PPP Phase 1 and providing a baseline architecture for Phases 2 and 3.
- 5G PPP Security Landscape (June 2017)[xx]
  Providing insights into how 5G security should be addressed in terms of "what" and "why".
- 5G Innovations for new Business Opportunities (March 2017)[xxi]
- Showing how the 5G PPP innovations go beyond early 5G deployments for the eMBB service class, and how all 5G service classes may be delivered over a scalable and cost-efficient network. It explains how 5G technological innovations transform the network into a secure, reliable and flexible orchestration platform across multiple technology and administrative domains.
- 5G PPP Cognitive Network Management for 5G (March 2017)[xxii]
  Presenting the novelties for network management in 5G.
- 5G PPP Vision on Software Networks (January 2017)[xxiii]
  Providing a first conceptual architecture seamlessly and flexibly combining SDN and NFV technologies for 5G.

Such collaborative work is notably leveraged to create industrial consensus and to support standardization work. At this stage, it is estimated that 5G PPP projects running under phase 1 have been at the origin of more than 320 industry contributions to standardization bodies and especially towards 3GPP (Third Generation Partnership Project), the key global standard development organization (SDO) for mobile communications.

5.1 5G PPP Phase 1

Phase 1 performed fundamental research for the 5th generation of communication networks. It started early 2015 with the implementation of 19 Projects[xxiv], many of them completing their work around mid-2017, while some continued until mid-2018. They provided important results on core 5G technologies and managed to develop solutions that are able to meet nearly all the performance KPIs for 5G.

Phase one projects contributed to 15 core areas of innovation[xxv], the “Golden Nuggets”, hereafter briefly reported.

5G System Design and Evaluation

a) *5G System, Functional, Logical and Physical Architectures*

The 5G system aims to provide a flexible platform enabling new business cases and models integrating vertical industries, such as, automotive, manufacturing, energy, eHealth, and entertainment. On this basis, network slicing has emerged as a promising future-proof framework adhering to the technological and business needs of different industries. In that context, network slicing has been researched and designed from an end-to-end perspective, spanning over different technology domains (e.g., core, transport and access networks) and administrative domains (e.g., different mobile network operators) including management and orchestration functions. More specifically, slice lifecycle automation was demonstrated with an architecture, functions and tools that implement cognitive procedures for all lifecycle phases: preparation phase, instantiation, configuration and activation phase, run-time phase, and decommissioning phase. Two fundamental technological enablers include softwarization, e.g., virtualization of network functions, as well as software-defined, programmable network functions and infrastructure resources. Other key elements constitute efficient management & orchestration procedures and protocols, all subject of in depth work. Finally, scalable, service-centric data analytics algorithms that exploit multi-domain data sources, complemented with reliable security mechanisms have been addressed for deploying customized network services with different virtualized NFs (VNF) on a common infrastructure in a trustworthy manner

At architectural level low latency has received particular attention. It requires data management (i.e. routed or processed) as close to where it is required i.e. either at the receiving end or at the source end). A low-latency architecture requires network intelligence location as close to the edge as possible, such that traffic which is expected to remain local never needs to travel towards the core of the network. It in this way minimizes transmission latency. Distribution of intelligence closer to the edge providing physical, logical and functional advantages as compared to the more conventional centralized architectural approach has been defined and characterized including a reference separation of the Control and User plane.

This also covers a 5G reference security architecture with focus on a logical and functional architecture. This focus is motivated by general trends such as network de-perimetrization as well as 5G systems' strong dependency on software defined networking and virtualization in general. The core of the proposed security architecture extends and revises the 3GPP security architecture from TS 33.401 to integrate domain concepts derived from 3GPP TS 23.101 to better support 5G trust models, going beyond “telecom” and “mobile broadband”. Strata allows characterizing different functional aspects and security feature groups are used to describe security objectives.

b) 5G Flexible Radio Access Network (RAN)

This critical part of 5G systems has received particular attention in 5G PPP phase one, in view of supporting the subsequent heavy work undertaken by 3GPP in this domain. The work has notably delivered:

- An agile resource management framework, built upon novel 5G aspects, i.e., diverse service requirements, slice service level agreements (SLAs), novel communication modes and dynamic radio topologies, which capitalizes on the flexible physical layer numerology. Within this framework, the developed interference management schemes are adaptive to changing radio topologies supporting movable access nodes. To address requirements of latency-critical services, dynamic traffic steering is developed for fast data routing on the RAN side without hard handovers, as opposed to legacy traffic steering schemes. Besides, RAN moderation schemes ensure the optimum number of active access nodes to fulfill service requirements while improving network energy efficiency.

- An initial access scheme based on service differentiation. The scheme enables both lower latency for mission critical services as well as high resource utilization. It allows disabling the always-on signals and instead use more dedicated signaling and self-contained transmission.

- mm-wave RAN integration for access, achieved with solutions involving tight interworking, multi-connectivity capabilities (to guarantee at least one access point with the desired level of performance) and lower-band integration. In the context of the overall RAN design, a new User Equipment (UE) state especially suited for bursty connections has been defined. The new state makes use of the stored RAN context and can thereby save Radio Resource Control (RRC) signaling which enables a better UE power consumption and lower latency.

- Low latency performance implementation in the context of demanding applications such as intelligent transportation systems (ITS) relying on high-speed, ultra-high reliable and secure digital connectivity. Low-latency as well as application initialization times has been demonstrated at the physical (PHY) layer, where a round-trip end-to-end (E2E) latency between UE and central office (CO) of 6.69 ms has been achieved, using ultra-high speed routing at the node router.

- Instantiation and management of different slices such that each slice may be potentially orchestrated in a different way, and thus be tailored to the requirements of a specific service. This requires the coordination of resources between different slices, which leads to the introduction of a new compound Software-Defined Mobile Network Control (SDMC) architecture.

- optimized dimensioning of transport requirements for different candidate 5G RANs, including below 6GHz massive Multiple Input – Multiple Output (MIMO) and mmWave RANs, and a variety of potential functional splits including L1 processing at the RRH, lower MAC and upper MAC splits.

- design and demonstration of advanced antenna systems for massive MIMO featuring 96 antenna elements and integrated L1 processing to reduce fronthaul data rate requirements by a factor of six to twelve, depending on the number of virtual ports employed.

c) 5G Spectrum Requirements and Candidate Bands

5G PPP has supported the 2016 proposal of the Radio Spectrum Policy Group[xxvi] (RSPG) on 5G “pioneer bands” with the following approach: (i) Low bandwidth spectrum (700 MHz) to enable 5G coverage to all areas, ensuring that everyone benefits; (ii) Medium bandwidth spectrum (3.4-3.8 GHz) to bring the necessary capacity for new 5G services mainly in urban areas; (iii) High bandwidth spectrum (26 GHz) to give ultra-high capacity for innovative new services, enabling new business models and sectors of the economy to benefit from 5G. In that context a joint 5G PPP approach has been worked out in support of the justification for spectrum beyond 6 GHz, clarifying the expected usage of different bands for different deployments and services. Different spectrum licensing and sharing options have also been studied taking into account the innovative properties of higher frequency bands. This latter part has notably been useful in the context of the second RSPG opinion[xxvii] outlining the licensing "toolkit" available to national regulators.

d) 5G Performance Evaluation Framework

A holistic and programme level 5G RAN performance evaluation framework has been developed for a numerical assessment of 5G KPIs and notably user data rates, reliability, control and user plane latencies, mMTC density or energy efficiency, as well as for comparison of technical solutions proposed for 5G. A visualization tool to illustrate the potential benefits that mm-wave cell deployment can offer has been developed with an open source software, and made available to all 5G PPP projects.

e) 5G Integrated Transport Networks, Fronthaul, Backhaul

Converged fronthaul/backhaul (FH/BH) services solutions based on active and passive optical technologies are needed to optimize resource of access point clusters with significantly higher capacity than in the case of 4G. Specifically, passive WDM-PON technology targets 25 Gbps/wavelength, colorless optical network unit (ONU) deployments and dynamic ONU switch-off for energy saving. Active optical technology is based on Time Shared Optical Networks (TSON). An adaptive, flexible and software-defined architecture for future 5G transport networks integrating multi-technology fronthaul and backhaul segments has been achieved. The architecture thus aims to enable a flexible and software-defined reconfiguration of all networking elements through a unified data plane and control plane interconnecting distributed 5G radio access and core network functions, hosted on in-network cloud infrastructure. This work has notably delivered: (i) an innovative architecture design for 5G transport networks targeting the integration of existing and new fronthaul and backhaul technologies and interfaces and (ii) a multilayer data plane architecture, including circuit- and a packet- switched paths.

5G Air Interface Innovations

A new radio interface covering new spectrum frontiers has been a key focus of 5G PPP early research activities. Main developments have been as follows:

a) 5G Multi-Service Waveform

New waveforms adapted for service coexistence below 6 GHz and overcome the demerits of Cyclic-Prefix Orthogonal frequency-division multiplexing (CP-OFDM - the 4G waveform) has been a strong focus in view of addressing poor spectral containment, lack of robustness in highly asynchronous and high mobility scenarios, as well as inflexibility for the support of diverse numerology. This was achieved by applying filtering techniques: subcarrier-wise filtered solutions and subband-wise filtered solutions. Common to all is the amelioration of spectral localization of the signal power, which improves the performance particularly for Massive Machine Communications (MMC), Mission Critical Communications (MCC) and vehicular (V2X) services and ensures an efficient coexistence of these services with Mobile Broadband (MBB) service. Whilst CP-OFDM was eventually adopted at 3GPP level for feasibility reasons, this work is particularly relevant for future evolutions of 5G radio systems and future releases of the 3GPP standard.

For services above 6GHz, radio-interface concepts and solution have been addressed. Twelve mm-wave challenges were analyzed and solution proposed based on: i) OFDM based waveforms, justified by a high spectral efficiency, easy integration with MIMO, lower complexity, time localization, and reasonable robustness to RF impairments, ii) enhancement of Low Density Parity Check (LDPC) codes and Polar codes with regard high throughput and robustness against hardware computation imprecision, iii) a flexible frame structure for TDD/FDD operations considering joint access and backhaul, low latency transmissions, as well as novel reference signal options to handle high mobility, phase noise, and CSI acquisition for large antenna arrays, iv) novel schemes for multiple access and initial access, v) multi-antenna solutions for hybrid beam-forming. Key components of the developed air-interface solution have been evaluated via simulator(s) as well as hardware-in-the loop trials. A dedicated channel model based on a comprehensive measurement campaign has been developed. Most of the achieved results have been reflected in subsequent 3GPP normative work.

b) 5G Flexible Interference Mitigation and Radio Resource Management (RRM)

Complementary work has addressed indoor and indoor/outdoor scenarios where capacity demands are the highest, but also where the proposed extended Dynamic Spectrum Allocation (eDSA) may be the most effective at exploiting co-operation across technologies and bands. As a result advanced RRM interacting with higher-level entities, enabling operator spectrum policy management for all types of regulatory regime have been designed with flexible and adaptive multi-RAT MAC for dynamic spectrum access and aggregation.

c) Technology Enablers for 5G RAN Platforms (HW & SW)

Enabling technologies are critical for 5G success. In 5G PPP, an architecture design for the transceiver of medium range base stations that supports three radio bands together with a design of a multiband high-power amplifier has been developed. The presented three-band transceiver solution considers radio bands defined for mobile communication (E-UTRA band 7 and 38 at 2.6 GHz and band 22 and 42 at 3.5 GHz) and one band between 2.7 and 2.9 GHz, Also, significant work has been done on context-aware, cognitive and dynamic HW/SW partitioning algorithm for 5G network elements. This algorithm exploits knowledge (e.g. prediction of a hotspot) derived by network and sensor measurements and decides upon the HW or SW execution of functions in order to fulfill and maintain the application goals. The algorithm leads to high flexibility, performance and energy efficiency. Moreover, full duplex technology provides gains in the user data rate of up to 50 % and in aggregated data rates (in a multiuser setting) of up to 21 %.

In addition, integrated management of physical and virtual infrastructures, which enables automated deployment of 5G infrastructures and services running on top of them, including virtualisation services, cloud computing, Mobile Edge Computing (MEC), SDN/NFV services and value-added services such as Service Function Chaining (SFC) have been addressed. Consequently, the creation and deployment time for infrastructures and their services are greatly reduced.

d) 5G Massive Channel Access

Commercialization and deployment of 5G systems need to support very high connection densities to make the Internet of Things serviceable. Massive connectivity is supported by new air interfaces that should optimise the available radio and infrastructure resources, spanning areas from protocol enhancements and radio resource management to waveform design. A new waveform design is proposed for asynchronous small packet transmissions in the uplink. Also, due to the superior spectral properties of certain waveforms, the need for tight temporal synchronization of users can be relaxed. This allows compressing or even avoiding broadcast messages, thus leading to energy and radio resource savings. In addition, new, "one-stage" access protocols are being developed, in which access notification and data delivery are performed in a single transaction by means of one or more consecutive packets or in a single transmission thereby reducing signaling overhead for short messages.

Network Management and Security Innovations

Applying advanced technologies and approaches at network management level is key to reduce OPEX of the target 5G infrastructure. The 5G PPP reached significant results in the following domains:

a) 5G Network Management

Autonomic network management has been progressed in order to improve network performance whilst reducing operational expenditures (OPEX). 5G autonomic network management is powered by artificial intelligence and extends the current 4G Self-Organising Network (SON) concept in the physical layer to both 5G physical and virtual domains. The work includes 5G network self-monitoring which collects and analyses performance metrics at multiple levels: physical infrastructure, virtual infrastructure and traffic flows with multi-tenancy awareness, thereby enabling timely situation awareness of 5G network infrastructures and services. A set of key, high-level Health of Network (HoN) metrics are modelled and introduced, and example HoN metrics include Virtual Infrastructure Vulnerability, Cyber-Attack Risk, and Video QoE. These innovative, customisable and extensible HoN metrics greatly facilitate speedy and more precise identification of common network problems.

At RAN level, a unified control and coordination framework for 5G heterogeneous RANs has been designed. It takes advantage of SDN for RAN programmability, in particular for efficient radio resource modelling and management, and flexible spectrum management. Major progress includes flexible RAN architecture design, radio resource abstraction, RAN data models and application program interfaces (APIs), virtualization and coordination framework, and flexible spectrum management. In that context, resource utilisation improvement and support of inter-operator spectrum sharing have been demonstrated which has led to subsequent take up at 3GPP level.

b) *5G Networks Security and Integrity*

A 5G Security Vision has been developed as well as a Technical Roadmap on security enablers for major areas of concerns (namely AAA, Privacy, Trust, Security Monitoring and Network management and virtualization) as confirmed by Open Consultation ran publicly on 5G. The researched security enablers come with open specifications for anyone interest to come up with its own implementation and are linked to major building blocks of the 5G Security Architecture defined and they contribute to. 5G Security enablers when software released (either open source or closed source based on decision left to enabler owner) also come with documentation (manuals) to integrate/deploy also make use of them within the 5G Security testbed according to use terms and conditions that apply. A 5G test-bed has been designed and set-up to satisfy the requirements of the 5G security enablers against the threats emerging from identified use cases. Launched in 2016 and based on three interconnected nodes provided by b<>com, VTT and Nokia.

Virtualisation and Service Deployment Innovations

Virtualisation and Software implementation of network functions is at the heart of the 5G promise to offer fully adaptable network environments tailored to the requirement of the specific tenants. In that context, this area was subject of massive R&I work under 5G PPP phase 1. Main achievements have been as follows:

a) *Network Softwarization and Programmability integrating SDN and NFV Technologies*

At RAN level, an SDN-based control plane unifying high capacity Point-to-Multipoint line of sight (P2MP LoS) mmWave radios and below 6GHz non line of sight (NLoS) radios has been developed. It features Openflow extensions for the mmWave and below 6GHz radios and common SDN controller implementing traffic engineering applications for the wireless backhaul, including load balancing, interference aware scheduling, and fast re-route.

At multi domain level, the split of Network Function Virtualization Orchestrator (NFVO) into Network Service Orchestrator (NSO) and Resource Orchestrator (RO) has been worked out as a solution for multi-domain interactions. This split of functionality has been complemented with a Slice as a Service (SlaaS) approach for multi-domain RO-RO interworking. While the ETSI NFV framework architecture has assumed so far that the NSO and RO functions are played by a single entity (the NFVO), the ETSI NFV has subsequently adopted a similar NSO-RO functional split for single administration. Initial design and deployment of a large scale test-bed connecting 13 sites, including 4 operators providing the connectivity backbone, and emulating realistic Internet topologies today has been achieved.

Additionally, a flexible NFV MANO Service Platform was developed for NFV that is built on a micro-service architecture and released as open-source software under the Apache 2.0 license. The Service Platform operates and manage the lifecycle of network service on top of a virtual infrastructure manager, like OpenStack. To this end, it deploys the virtual network functions as virtual machines and steers the traffic by implementing service function chains. In that respect, complex services can be built through the "chaining" of these Micro-VNFs, with different virtualization approaches used to support these micro-VNFs.

b) E2E Orchestration in Single and Multi-Domains 5G Virtualized Networks

From an end to end perspective and in view of providing multi domain interoperability and resource "stitching", the multi-domain orchestration process has been broken down into the main functions relevant to a multi-provider multi-domain environment: discovery, bilateral negotiation, provisioning and assurance stages with their corresponding multi-domain reference points in a detailed multi-domain orchestration architecture. A proof of concept prototype of the multi-provider, multi-domain orchestration as an integration of the major concepts from several projects has been developed with advanced transport control.

Similarly, solutions have been proposed to allow infrastructure owners to dynamically share (control, manage, orchestrate) their resources, virtual and physical, in an isolated manner (network slices), and among several network operators to offer different customized services to their end customers. To that end, an Open Access Manager (OAM) module has been developed which is responsible for the lifecycle management of network slices including communications with network, cloud, or device controllers for creation and operation of a slice and exposing it to upper layers for dynamic service provisioning.

This is complemented with service and domain aware orchestration which is responsible, among other functions, for placing virtualized functions in the most appropriate location. Herein, it takes into account the requirements of the corresponding service that needs to be satisfied, the constraints on the placement of functions that interact with each other and the features of the underlying infrastructure. Orchestration takes place end-to-end, spanning the whole mobile network from the user to the packet data network respectively to the service provided for the user. Accordingly, end-to-end orchestration typically involves multiple stakeholders spanning infrastructure provider, mobile service provider and tenant, allowing different network slices to have their own Management and Orchestration (MANO) stack implementation.

c) Programmable Industrial Networks

Applicability of 5G technologies to vertical industries is at the heart of the European 5G strategy. In that context, SDN & NFV ecosystem, based on open, modular and secure framework have been implemented to showcase a prototype for intra-domain and inter-domain scenarios in real wind parks as a representative use case of industrial networks. The wind-park control network is very representative of a professional application as wind energy has now established itself as key for sustainable energy generation. With lower capital expenditure and operational expenditure costs in control network infrastructure, the validation of the economic viability of the approach has been demonstrated. Further applicability in other industrial domains are expected to be demonstrated as follow up.

d) Flexible and Agile Service Deployment

Fast service deployment is needed in 5G considering the very large number of use cases and related service requirements that are expected. Service Platform developments have been complemented with a Service Development Kit (SDK) that aims at fast implementation, testing, and debugging of virtualized network functions and services. The SDK supports the creation of function and service descriptors as well as service packages uploaded to the Service Platform and used to manage the lifecycle of complex network service. It also offers features to test, profile, and debug network services locally by using a Service Platform emulator that mimics the behavior of the actual Service Platform locally, e.g. on a developer's laptop. The knowledge gained by these local tests simplifies the function and service development, shorten the time-to-market, and at the same time, increases the quality of the resulting product. The SDK interconnects tightly with the Service Platform and allows monitoring running services in real time. To this end, it enables the developer to collect important data and offers tool to analyze the data in order to debug or improve the service, for example in terms of performance.

In complement, a framework to automatically map service level Key Performance Indicators (KPIs) to the platform level parameters in the host compute environment have been developed. The framework enables the identification of platform features, which most significantly influence the KPIs for a given workload under test.

In conclusion, phase one has addressed a multiplicity of 5G enabling technologies and has demonstrated their applicability in view of reaching the main 5G target KPI's, notably at radio level. Table 3 below provides a sample of achieved results in that domain:

Key Performance Indicator	**Baseline/Target**	**Demonstrated**
Data rates	20 Gb/s DL - 10 Gb/s UL (target)	21 Gb/s DL - 12 Gb/s UL
User Plane Latency	1 ms (ITU target)	0,76 ms
User Data Rate	100 Mb/s (LTE) dense urban	> 300 Mb/s
Wireless backhaul	N/A	4Gb/s at 60 GHz
Cell edge throughput	15 Mb/s LTE average	170 Mb/s

Interference cancellation	Static TDD	60% gain with Dynamic TDD
Aggregation of multiple radio access techs	N/A	Demonstrated with flexible RRM (radio resource management)
Energy savings	LTE	RAN savings up to 66%
Energy efficiency	Current class of devices	31 % with integrated antenna/amplifiers
Quality of service	Video transmission corrupted by Intercarrier interference at very high speeds	600 Km/h perfect video transmission demonstrated with new waveform/MAC
Positioning	N/A	<1m Proof of concept
Channel bandwidth	20 MHz contiguous (LTE)	400 MHz contiguous with flat response at 26 GHz implemented in trial

Table 3. Sample radio results achieved in phase 1

5.2 5G PPP Phase 2

Phase 2 capitalises on phase one developments to move towards Proof of concepts and trials in the context of a multiplicity of vertical use cases. It started in June 2017, with 22 new 5G PPP projects[xxviii] complemented by 2 projects dealing with international collaboration with Taiwan. Most Phase 2 projects terminate in 2019, whilst a few will continue in 2020.

The phase 2 move towards use cases and the 5G user community has been particularly successful, considering that 62% of participants in phase 2 projects were newcomer to 5G and not participating in Phase 1 projects. This is a positive indication of the 5G interest to the vertical community in Europe.

Phase 2 projects cover eight vertical clusters: Automotive, Energy, Health, Industry, Media and Entertainment, Public Safety, Smart Cities, Transport and Logistics. The various projects cover different 5G KPI, as a function of the eMBB, URLLC, or mMTC requirement they have to satisfy for the considered use cases. The peak of PoC’s and trials targeting verticals occurs with Media and

Entertainment. One reason for this is that eMBB (enhanced Mobile Broadband) is among the first services to be supported with early 5G deployment.

Cities are as well an important focus, with many trials and pilots directly or indirectly contributing to the 5G smart city ecosystem. About 50% of the implemented projects target eMBB use cases whilst mMTC and URLLC use cases are covered by about 25% of the projects each. Focussing on Smart Cities, trials will take place in 2019 and 2020. This timing is compatible with the availability of technologies that support the 5G New Radio, core network functions and the user equipment, and is in line with the early trial objectives set out in the 5G Action Plan. Another important aspect in this context is the provision of radio spectrum for 5G, which may somehow vary across EU[xxix]. Altogether, phase 2 projects account for 63 PoC's and trials in 38 cities across 13 EU countries. Figure 2 below illustrates the typology of experiments and their locations in member States whilst figure 3 illustrates the city locations for PoC's and trials across the 8 vertical clusters supported by Phase 2 projects

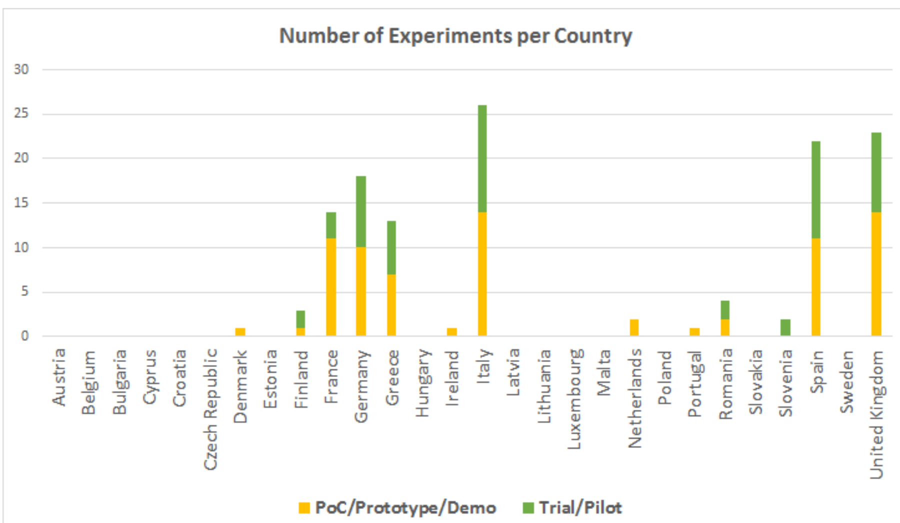

Figure 2: Typology and location of Phase two POC's and trials

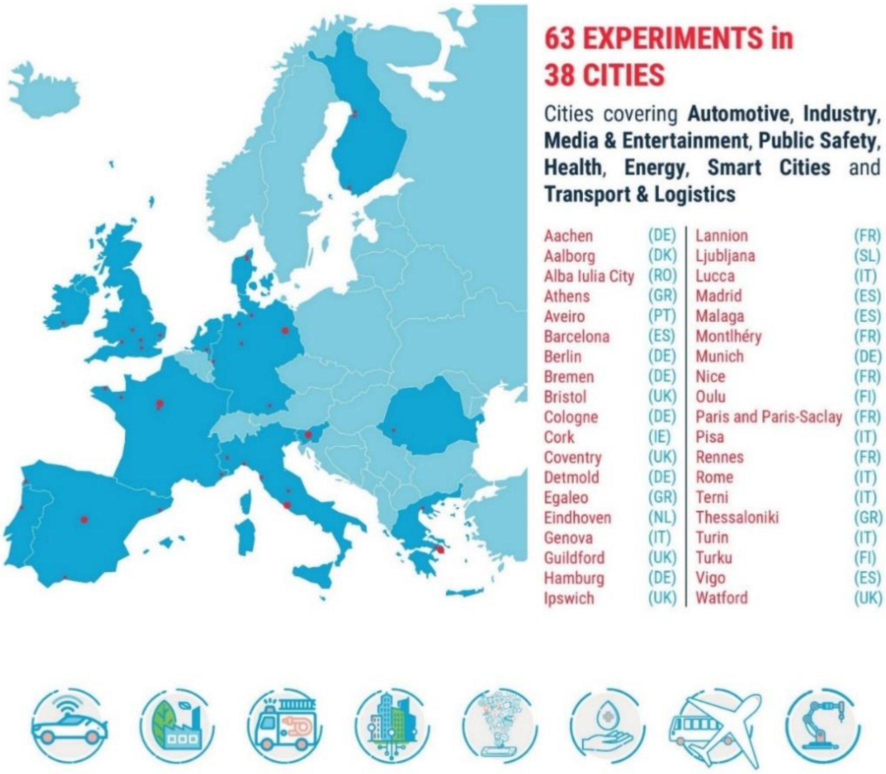

Figure 3: European cities covered by 5G PPP phase 2 PoC's and trials

5.3 5G PPP Phase 3

Phase 3 has two objectives: i) to support the development and rollout of 5G innovation and validation platforms across Europe in view of fostering 5G acceptability in a wide variety of business sectors from the technological and business point of view and, ii) to support the European R&I ecosystem to prepare longer term evolution of 5G and "beyond 5G" systems.

The 5G PPP phase 3 has been structured in steps as follows:

- the setup of and end to end 5G platform that may be used by verticals to run large scale validation of their use cases, using at least 5G Release 15 compatible

technology, hence with characteristics very close to commercially deployed platforms. Under this step, 3 projects have been selected and started in June 2018;
- the setup of dedicated large scale pilots for Connected and Automated Mobility, taking into account the strategic role identified for this vertical at the level of the 5G AP, and supporting the Member States commitments to make available cross border corridors for 5G based CAM. Another set of 3 projects started in November under this step
- The implementation of large-scale trials and pilots for amultiplicity of verticals, running on top of the selected end to end 5G validation platforms. This step is to be implemented early 2019;
- the launch of a longer term 5G "long term evolution" initiative, in view of paving the way towards systems beyond 5G with a medium to long term approach and taking into account technologies not yet addressed under the 5G PPP. This step is to be implemented in 2019.

The last work programme covering the year 2020 will complement these phase 3 initiatives.

i) 5G end-to-end test and validation platforms.

The complexity of 5G and the multiplicity of technologies integrated under one single platforms call for the availability of end to end 5G platforms to validate the vertical use cases of interests. The main objective is to actually demonstrate with user pilots the core 5G capability, namely that one single infrastructure can instantiate several networks serving different requirements, even if conflicting, with shared and isolated resources. In that context, the target is to implement a multiplicity of concurrent vertical use cases on top of one single end-to-end platform, such that the overall performance can be tested and validated in close to operational conditions. This call for availability of equipment with characteristics that are close to equipment actually deployed in operational networks, and the selected platforms will first implement Release 15 technology and gradually upgrade with Release 16 technology as the specifications become available.

The 5G Infrastructure PPP Phase 3 platforms projects[xxx] (2018-2021) are:

- 5G EVE
- 5G VINNI
- 5GENESIS

They all started in July 2018 provide large-scale end-to-end 5G validation network infrastructure, covering about 20 EU sites and nodes on a pan-EU basis. This infrastructure will provide the adequate level of openness to make it possible for vertical industries to test their innovative 5G business cases using ad-hoc network resource control in an end-to-end interoperability framework.

The key platforms and cities of the PPP Phase 3 projects are outlined in figure 4 below.

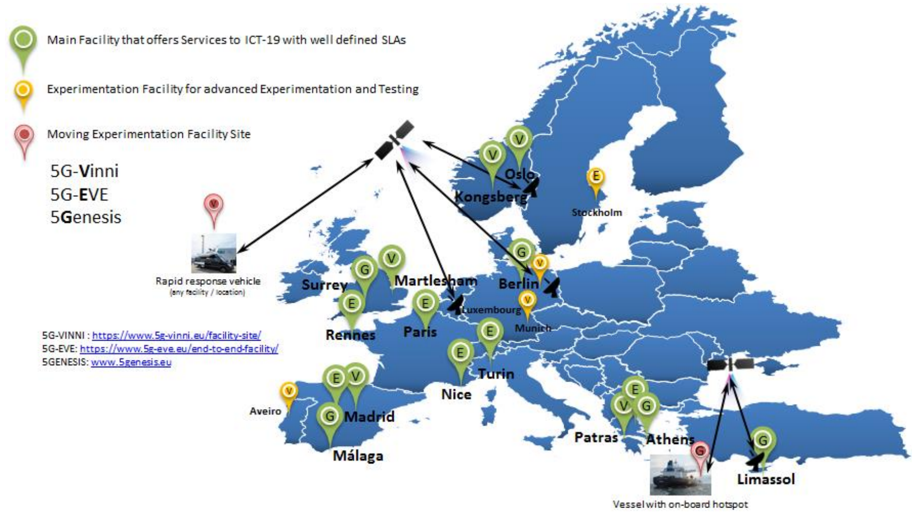

Figure 4: 5G PPP Phase 3 Platforms Projects – Site distribution

The key capabilities and features are summarized in the Table below. It may be noted that (1) capabilities will be incrementally added until the end of the projects; (2) interworking refers to interconnection of two or more sites to provide unified service(s) in the 5G E2E facility and interconnection does not assure interworking; (3) integration will be developed with Vertical Pilots projects; (4) exact time line will be communicated after selection of the vertical projects running on top of the platforms. The notes (2), (3) and (4) apply as reported in specific corresponding capabilities rows.

Platforms Capabilities	5G-EVE	5G-VINNI	5GENESIS
Rel15-5GNR in Non Standalone Alone (NSA) mode	Turin, Madrid, Paris, Athens *January 2020*	Oslo, Kongsberg, Martlesham,	Athens, Berlin, Limassol, Malaga, Surrey

		Patras, Madrid, Aveiro	
Rel15-5GNR with Rel15-5GCore in Standalone Alone (SA) mode[(4)]	Turin, Madrid, Paris, Athens *June 2021*	Oslo, Kongsberg, Martlesham, Patras, Madrid, Aveiro. *After Jan2020*	Athens, Malaga, Berlin, Surrey
Rel16-5GNR and 5GCore (NSA or SA)[(4)]	Turin, Madrid, Paris, Athens *June 2021*	Oslo, Kongsberg, Martlesham, Madrid, Patras *After Jan2020*	Surrey
Network Slicing as a service[(3)]	-	Oslo, Kongsberg, Martlesham, Patras, Madrid, Aveiro	Athens, Malaga, Surrey
Customized network slice (e.g. SFC, security, enhanced Cloud access) [(3)]	Turin, Madrid, Paris, Athens *June 2021*	Oslo, Kongsberg, Martlesham, Patras, Madrid, Aveiro	Athens, Berlin, Limassol, Malaga, Surrey
Hosting of 3rd party VNFs[(3)]	Turin, Madrid, Paris, Athens. *January 2020*	Oslo, Kongsberg, Martlesham, Patras, Madrid, Aveiro	Athens, Berlin, Limassol, Malaga, Surrey
Interworking[(2)] with other platform facilities[(3)]	Turin, Madrid, Paris, Athens *June 2021*	Oslo, Kongsberg, Martlesham, Patras, Madrid	Athens, Malaga, Surrey
Integration of additional gNB to platform facility[(3)]	Turin, Madrid, Paris, Athens *January 2020*	Oslo, Kongsberg, Martlesham, Patras, Madrid, Aveiro *After Jan2020*	Athens, Berlin, Limassol, Malaga, Surrey
Edge Computing	Turin, Madrid, Paris, Athens *January 2020*	Madrid, Aveiro, Oslo, Kongsberg, Patras, Martlesham (TBD). *After Jan2020*	Athens, Malaga, Surrey
Distributed Data fabric service for analytics	-	Oslo, Kongsberg, Patras (TBD), Madrid. *After Jan2020*	Athens

3.5 GHz 5G Radio	Turin, Madrid, Paris, Athens *January 2020*	Oslo, Kongsberg, Martlesham, Patras, Madrid, Munich, Aveiro	Athens, Malaga, Surrey
26 GHz 5G Radio		Oslo, Kongsberg, Martlesham	Surrey
Millimeter wave for Backhaul		Patras	Surrey
End UserTesting	Turin, Madrid, Paris, Athens *January 2020*	Oslo, Kongsberg, Martlesham, Patras, Madrid	Athens, Berlin, Limassol, Malaga, Surrey
Automatic testing framework	Turin, Madrid, Paris, Athens	Oslo, Kongsberg, Martlesham, Patras, Madrid	Athens, Malaga, Surrey

Table 3: 5G PPP Phase 3 Platforms Projects – Capabilities/Features/

When implementing vertical use cases large-scale pilots on top of these platforms, a key objective will be to satisfy the network resource control by multiple tenants with the adequate level of resource visibility/control required by these tenants. Another important aspect will be to demonstrate composability of resources across multiple domains and also the right level of service/data isolation between the different use cases ran in different slices. These pilots are expected to start their implementation in the second half of 2019.

i) Pilots over cross border corridors for Connected and Automated Mobility

Three projects started[xxxi] under this initiative:

- 5G CARMEN;
- 5G CROCO
- 5G MOBIX

These projects only cover a subset of the currently existing ten cross border corridors made available by Member States. 5G CARMEN covers the Brenner Corridor over IT-AT-DE, 5G CROCO covers the Metz-Merzig-Luxembourg corridor linking FR-DE-LU; 5G MOBIX covers the Porto-Vigo, Evora-Merida corridor linking PT-ES and the Greece-Turkey corridor with and 8km segment across the border. The main target is to leverage vehicle connectivity to create complete ecosystem around cars, serving not only safety related applications but a rich blend of application including maintenance, insurance, infotainment, driver's assistance and autonomous driving. The projects take a holistic perspective covering V2x scenarios, namely vehicle to vehicle (V2V), vehicle to infrastructure (V2I), vehicle to network (V2N), vehicle to pedestrian (V2P). This latter mode is by far a priority for safety services considering that the highest number of road fatalities concerns collisions between cars and pedestrians. In that particular case, the possibility to establish ultra-low latency connectivity with user smart phones is of the essence.

More generally, these projects are addressing a multiplicity of issues such as:

- Use of hybrid new radio to validate 5G radio in CAM context

- Multi domain service orchestration for cross domain seamless service provision

- Distributed multi layer embedded cloud for low latency and multi service support;

- Novel type of services paving the way towards Release 16 capabilities such as remote driving, see through, high density platooning, share my view scenarios as typical use cases defined by 3GPP.

The projects are also expected to assess the economic feasibility of the considered scenarios and will evaluate the interworking and co-existence/complementarity scenarios with safety dedicated technologies such as ITS-G5. In view of addressing more cross border corridors and complementary innovation, the Commission proposes complementary CAM actions for the last work programme of Horizon 2020, with target implementations in 2020. Finally, the European Commission has proposed CAM follow up actions for operational deployment of 5G technology along main transport paths under the CEF2[xxxii] proposals of the next Multi Annual Financial Framework (MFF).

6 Spectrum and Standards: Key Enablers

As identified in the 5G Action Plan, the early availability of spectrum is critical to enable 5G deployment in Europe. The identification of 5G spectrum above 24 GHz (i.e. in the millimetre wave range) is notably framed by the ITU preparatory process, which has identified a number of candidate bands between 24.25 and 86

GHz to be studied until the next World Radiocommunication Conference in 2019 (WRC-19).

Whilst the 28 GHz band was not part of the bands to study by the last WRC-15, several nations (US, South Korea, Japan) have already decided to assign this band for early 5G introduction, in view of driving the international spectrum policy agenda. The US FCC declared its intentions to license the 28 GHz band for 5G already in summer 2016 under the “Spectrum Frontiers” initiative.

Based on these fast international developments, Europe addressed the 5G spectrum issue through the Radio Spectrum Policy Group (RSPG). The RSPG reached conclusions in its Opinion on 5G Spectrum, adopted in November 2016 and supported by the European industry, that there was a need to select a set of pioneer bands for early 5G trials and pilots, in order to ensure appropriate early commercial deployment in 2020. The 26 GHz band is one of these pioneer bands, together with the 700 MHz and 3.6 GHz bands. Having a band in the millimetre wave range is essential to cater for the very high data speeds targeted by 5G, thanks to the considerably larger bandwidth it can offer compared to the lower spectrum bands. Its compatibility for the use by 5G is under study by the CEPT in view of further spectrum harmonisation initiative of the Commission planned for 2019. These positive developments do all support the ambitious deployment objectives of the 5G AP. Amongst the other key ITU members, China is also promoting the 26 GHz band in the international context, whilst the 3,5 Ghz band enjoys a very good level of support globally.

In Europe, recent spectrum developments have shown that member States are now moving forward with assignments of 5G spectrum. Several MS have already launched auctions, whilst a significant number of auctions are being planned for 2019 or being prepared through national consultations. The Commission through the European 5G observatory[xxxiii] launched in September 2018 consistently monitors the spectrum status in Europe. As indicated in the context of the launch of 5G PPP end to end trial platforms, it may be seen that 3,5 GHz and 26 Ghz are already available in some MS for test and pilot experiments. Early availability of these bands is indeed key to stimulate the development of a device ecosystem and to allow ambitious trials with vertical users to be set up. 5G PPP R&I initiatives will hence actively leverage spectrum availability in leading Member States.

Similarly, global standards are key to support the ambitious use cases targeted by 5G. For the first time in the history of mobile communications, the prospects of one single 5G global standard is real, considering that all key stakeholders and nations have joined forces in 3GPP to define a global standard.

3GPP initiated the development of the 5G standard in September 2015, with an inception workshop in Phoenix, USA. The first version of the standard was released in June 2018, under the Release 15, with a specification that covers the Non Standalone (NSA) and Standalone (SA) options. NSA implies that the 5G-access node relies on a 4G core or on another 4G eNodeB to establish the connection. This is the deployment option selected for almost all the early deployment scenarios as it allows operators to capitalise on earlier 4G investments. The SA option relies on a complete 5G gNode B and a 5G core. Few operators, notably China Mobile, intend to proceed with SA deployment at this stage.

The fast development of this first release was pushed by the aggressive deployment agenda of operators from the US and Asia. Consequently, the first release has focused on the eMBB use case and on the "New Radio" (NR) specification, in view of the high rate high capacity options contemplated by these operators. The standard cover notably:

- The NR functionalities for enhanced mobile broadband (eMBB) and ultra-reliable low-latency-communication (URLLC) as defined in [TR38.913]. URLLC focus has primarily been on low latency. NR specification consider frequency ranges up to 52.6 GHz. The NR functionalities have been designed to be forward compatible and allow for smooth introduction of additional technology components and support for new use cases. Backward compatibility of the NR to LTE is not required.
- Layer 1 and Layer 2 user plane specifications include a common part to all supported architecture options. However and for some aspects, Layer 1 and Layer 2 user plane specifications are different between single connectivity and Dual Connectivity options.
- Several connectivity options and scenarios as defined in TR38.801 and corresponding to either NSA or SA options are considered for this normative work. These scenarios envisage several configurations to link (or not) to an

existing 4G infrastructure, hence providing maximum flexibility to operators to implement 5G as a function of their existing 4G deployment status.

The next stage of development of the standard will take place under Release 16 that started in June 2018 for the normative phase. This is illustrated in figure 5 below:

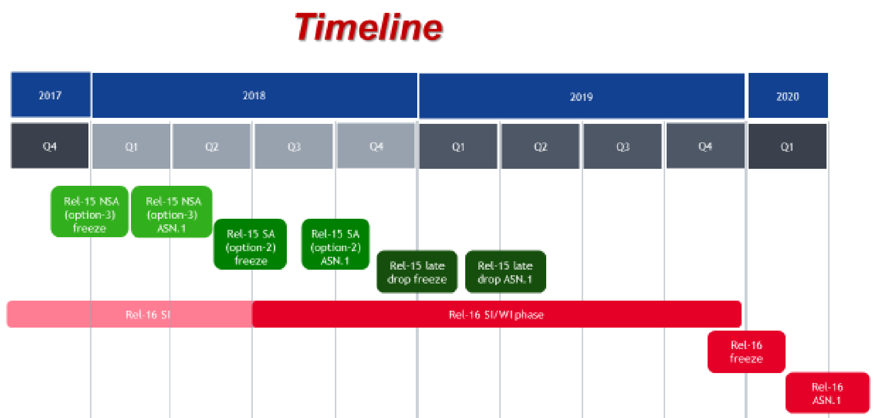

Figure 5: 5G standardization time frame at 3GPP level (source, 3GPP)

Release 16 has two aspects on its agenda:

i) A 5G ***expansion,*** the main extensions being:

- Vehicle to X (V2X), moving NR into V2X in complementary mode
- Industrial IoT
- Ultra-Reliable Low-Latency Communication (URLLC) enhancements, notably the reliability part which is critical for mission critical applications
- Unlicensed spectrum operation
- NR-Broadcasting, though only at study stage

- Non terrestrial networks (NTN), namely for the satellite community

ii) At the same time important work is planned to improve 5G ***efficiency*** through:

- Interference Mitigation
- 5G Self-Organising Networks (SON) & Big Data
- 5G Multiple-input multiple-output (MIMO) enhancements
- 5G Location and positioning enhancements (also key for industrial applications)
- 5G Power Consumption improvements
- Dual Connectivity enhancements
- Device capabilities exchange

Release 16 is hence important to make 5G fully compatible with vertical use cases. In particular, the work under the "5G expansion" work item relates to important use cases, notably automotive, Industry 4.0 and factories, but also healthcare and energy. 5G PPP phase 2 and phase 3 projects will both contribute to and benefit from these important standardisation developments.

7 Conclusion

The European Commission has clearly identified 5G as a key infrastructure to fulfil the wider policy objectives aiming at a modernised digital industry and economy. Bold support has been provided to industry through a structured and targeted research programme responding to policy initiatives and aiming at accelerating the availability of 5G in Europe. Moving towards user pilots is now of paramount importance, and the framework conditions to make this happen are rapidly developing (availability of technology, frequency bands, standards, regulations). It is now up to the industry to seize the opportunities and to develop ambitious business plans to make Europe a lead market of the 5G era.

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5G PPP project a coherent set of complementary initiatives delivering a consistent set of important results. Their efforts in structuring and analysing the overall contribution and impacts of the projects at programme level have been essential to provide the overview reported in this paper.

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