Leading Innovations Towards 5G

Europe's Perspective in 5G Infrastructure Public-Private Partnership (5G-PPP)

Jose Alcaraz-Calero[1], Ioannis-Prodromos Belikaidis[2], Carlos Jesus Bernardos Cano[3], Pascal Bisson[4], Didier Bourse[5], Michael Bredel[6], Daniel Camps-Mur[7], Tao Chen[11], Xavier Costa-Perez[6], Panagiotis Demestichas[8], Mark Doll[9], Salah Eddine Elayoubi[10], Andreas Georgakopoulos[2], Aarne Mämmelä[11], Hans-Peter Mayer[9], Miquel Payaro[12], Bessem Sayadi[5], Muhammad Shuaib Siddiqui[7], Miurel Tercero[13], Qi Wang[1]

[1]University of the West of Scotland, UK; [2]WINGS ICT Solutions, Athens, Greece; [3]Universidad Carlos III de Madrid, Madrid, Spain; [4]Thales Group, Paris, France; [5]Nokia Bell Labs, Paris, France; [6]NEC Europe, Heidelberg, Germany; [7]Fundacío i2CAT, Barcelona, Spain; [8]University of Piraeus, Piraeus, Greece; [9]Nokia Bell Labs, Stuttgart, Germany; [10]Orange Labs, Paris, France; [11]VTT, Oulu, Finland, [12]CTTC/CERCA, Barcelona, Spain; [13]Ericsson, Kista, Sweden;

***Abstract*—The paper elaborates on the technological and architectural innovations researched and developed by 5G-PPP Phase 1 projects and covering innovation areas such as 5G system design and evaluation, novel air interfaces, network management and security as well as virtualization and service deployment aspects.**

Keywords— 5G-PPP, 5G system design, air interfaces, network management, security, virtualization

I. Introduction

5G is the next generation mobile network that enables innovation and supports progressive change across all vertical industries and our society [1]. Through Radio Access Network (RAN) design and an orchestrated end-to-end architecture, it has the potential to boost innovation and generate economic growth across all verticals. This paper introduces the 5G Infrastructure Public-Private Partnership programmatic perspectives and introduces the 15 Golden Nugget boxes which have been proposed by the 5G-PPP Phase 1 projects.

II. 5G Global Initiatives

Since the launching of the 5G-PPP programme in Europe, other initiatives across the globe have taken place. For instance, S. Korea has launched the 5GForum program, while Japan is very active in 5G operations through the ARIB-5GMF. Also, in the USA there is the 5G Americas initiative, and China promotes 5G research through IMT2020. Therefore, 5G is globally represented by major initiatives and bodies which are promoting research and development in such aspects.

III. 5G-PPP Programme Main innovations and Opportunities

The 5G-PPP programme in Europe includes a wide gamut of collaborative projects which are driven by major vendors and operators and focus on important technological innovations which help in reaching the key performance targets for the 5G service classes including enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (URLLC), and massive machine type communications (mMTC) [24]. These performance levels ensure an unprecedented experience for end users including high data rates, reduced end-to-end latency, massive connectivity, ultra-reliability and support for very high mobility, ubiquitously. Thousands of researchers and developers across Europe are working on innovative solutions for the definition of 5G architecture, of a flexible RAN, new spectrum opportunities, fronthaul and backhaul solutions, virtualized networks etc. Results and demonstrations of all these aspects are extensively reported in publications and event presentations in order to disseminate valuable findings and strengthen Europe's impact towards 5G developments.

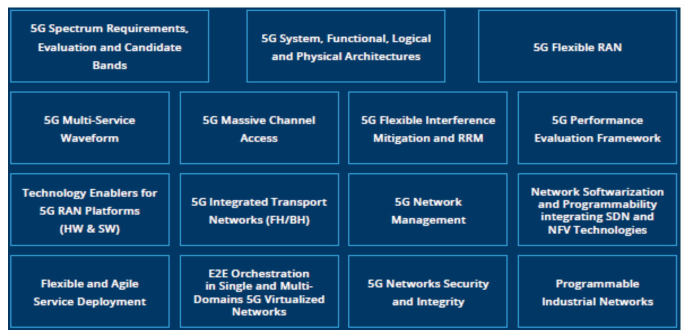

Fig. 1. 5G-PPP Phase 1 projects Golden Nugget boxes [1]

IV. 5G System Design and Evaluation Aspects

This section stresses on the innovations of 5G system design and evaluation. The following Golden Nuggets are part of this section:

A. 5G System, Functional, Logical and Physical Architectures

CHARISMA project [10] takes into account the fact that at the architectural level, achieving low latency (service level) requires data to be handled (i.e. routed or processed) as close to where it is required (i.e. either at the receiving end or at the source end). Indeed, this implies that a low-latency architecture requires network intelligence to be located as near to the edge as possible, such that traffic which is expected to remain local never needs to travel towards the core of the network; and in this way minimizes transmission latency. Thus CHARISMA's distribution of intelligence closer to the edge provides physical, logical and functional advantages as compared to the more conventional centralised architectural approach. Moreover, 5G-ENSURE [26] delivers a 5G reference security architecture with focus on a logical and functional architecture and omits (most) aspects related to physical/deployment 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. Specifically, the core of the 5G-ENSURE 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 are used to characterize different functional aspects and security feature groups, finally, are used to describe security objectives.

B. 5G Flexible RAN

The 5G-XHAUL project [2] proceeds to the 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. Also it proceeds to the design and demonstration of an advanced antenna system 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. Moreover, CHARISMA stresses on the low latency performance indicator and mentions that a key driver for 5G is the emergence of intelligent transportation systems (ITS), particularly relying on high-speed, ultra-high reliable and secure digital connectivity. Intrinsic to such ITS infrastructure is low-latency as well as application initialization times. At the physical (PHY) layer, a round-trip end-to-end (E2E) latency between user equipment (UE) and central office (CO) of 6.69 ms has recently been achieved, using ultra-high speed routing at the TrustNode router. Also, the 5G-NORMA project [12] instantiates 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. Furthermore, the mm-wave RAN integration for access is the focus of mmMAGIC project, proposing solutions like: tight interworking, multi-connectivity choices and low-band integration [20]. In addition to work on overall RAN design [21], METIS-II has already at an early stage investigated a new UE state especially suited for bursty connections. The new state makes use of the stored RAN context and can thereby save RRC signaling which enables a better UE power consumption and lower latency [22]. Further on, MEITS-II has developed a service differentiation initial access scheme. The scheme enables both lower latency for mission critical services as well as high resource utilization. METIS-II has strived to enable a lean design of 5G by disable the always on signals and instead use more dedicated signaling and self-contained transmission. This can for example be reference signals that are not always on and/or just part of the bandwidth [23]. In addition, METIS-II has developed an agile resource management framework, which is built upon novel 5G aspects, i.e., diverse service requirements, slice service level agreements (SLAs), novel communication modes and dynamic radio topologies, and capitalizes on the flexible physical layer numerology [38]. Within this framework, the developed interference management schemes are adaptive to changing radio topologies based on 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.

C. 5G Spectrum Requirements, Evaluation and Candidate Bands

Early access to the necessary frequency bands is critical for Europe to perform 5G technology tests, trials, pilots and for the early launch of commercial products services. The news release of the Radio Spectrum Policy Group (RSPG) states the following on 5G "pioneer bands": (i) Low bandwidth spectrum (700 MHz) which can enable 5G coverage to all areas, ensuring that everyone benefits; (ii) Medium bandwidth spectrum (3.4-3.8 GHz) which will bring the necessary capacity for new 5G services 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 this area METIS II has defined a joint view of the partners on spectrum aspects, in particular on the justification for spectrum beyond 6 GHz, and the expected usage of different bands for different deployments and services, as well as expected spectrum licensing and sharing options [34].

D. 5G Performance Evaluation Framework

The mmMAGIC project has developed a visualization tool to illustrate the potential benefits that mm-wave cell deployment can offer [19]. The tool is developed on blender which is an open source software. METIS-II developed a holistic 5G RAN performance evaluation framework, which can be used for a fair numerical assessment of 5G KPIs (e.g. 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. Instructions and corresponding evaluations are provided for each KPI[35]-[37].

E. 5G Integrated Transport Networks (FH/BH)

The 5G-XHAUL project [2] investigates active and passive optical technologies for converged fronthaul/backhaul (FH/BH) services. 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) [29]. Moreover, the goal of the 5G-Crosshaul project [5] is to build an adaptive, flexible and software-defined architecture for future 5G transport networks integrating multi-technology fronthaul and backhaul segments. The 5G-Crosshaul 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. Based on this, on the first year 5G-Crosshaul has completed two important milestones: (i) an innovative architecture design for 5G transport networks targeting the integration of existing and new fronthaul and backhaul technologies and interfaces [6] and (ii) development of a multilayer data plane architecture, including circuit- and a packet- switched paths [7].

V. 5G Air interface Innovations

This section stresses on the innovations of 5G air interface. The following Golden Nuggets are part of this section:

A. 5G Multi-Service Waveform

The FANTASTIC-5G project works on 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) in terms of poor spectral containment, lack of robustness in highly asynchronous and high mobility scenarios, as well as inflexibility for the support of diverse numerology. This is obtained by applying two categories of filtering: 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 [3].

For services above 6GHz, the mmMAGIC project [15] has developed radio-interface concepts and solution. Twelve mm-wave challenges were analysed [18]. The mmMAGIC air-interface solution includes: i) OFDM based waveforms, particularly attractive mainly due to high spectral efficiency, easy integration with MIMO, lower complexity, time localization, and decent robustness to RF impairments, ii) enhancement of LDPC 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 has been evaluated via the project owned simulator(s) as well as hardware-in-the loop trials. In order to understand high frequencies, mmMAGIC developed its own channel model based on its highly ambitious measurement campaign [16]. The important findings have been continuously disseminated and cited in 3GPP and ITU-R contributions from the mmMAGIC project partners.

B. 5G Flexible Interference Mitigation and RRM

The SPEED-5G project [27] SPEED-5G investigates indoor and indoor/outdoor scenarios where capacity demands are the highest, but also where the proposed extended Dynamic Spectrum Allocation (eDSA) will be the most effective at exploiting co-operation across technologies and bands. As a result the project focuses on advanced RRM interacting with higher-level entities, enabling operator spectrum policy management for all types of regulatory regime. Also aspects on flexible and adaptive multi-RAT MAC for dynamic spectrum access and aggregation are investigated.

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

Flex5Gware [8] researchers have proposed 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 with an output power of 53 dBm. 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, which is in discussion to become available during the next years. 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 developed in Flex5Gware 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, the project SELFNET [9] achieves 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). Consequently, the creation and deployment time for infrastructures and their services are greatly reduced, from days to minutes.

D. 5G Massive Channel Access

The FANTASTIC-5G project works also on non-scheduled access for massive MTC which is motivated by the fact that the commercialization and deployment of 5G systems is driven by the 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 [3]. 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 [4].

VI. Network management And Security Innovations

This section stresses on the innovations of network management and security. The following Golden Nuggets are part of this section:

A. 5G Network Management

The SELFNET project contributes to autonomic network management in order to improve network performance whilst reducing operational expenditures (OPEX). 5G autonomic network management is powered by artificial intelligence and will substantially extend the current 4G Self-Organising Network (SON) concept in the physical layer to both 5G physical and virtual domains. Moreover, SELFNET proposes 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.

The COHERENT project aims to develop a unified control and coordination framework for 5G heterogeneous RANs, with the emphasis on SDN for RAN programmability, in particular efficient radio resource modelling and management, and flexible spectrum management. In the first year of the project, COHERENT has made a concrete progress on flexible RAN architecture design, radio resource abstraction, RAN data models and application program interfaces (APIs), virtualization and coordination framework, and flexible spectrum management. The Golden Nugget of the COHERENT project in the first project year is a novel control and coordination architecture, which is presented in [25]. The Golden Nugget includes two innovations: i) We have designed and developed novel control and coordination architecture, mechanisms and APIs, protocols and algorithms to enable RAN programmability and significantly improve resource utilization and services in next generation heterogeneous radio access networks. ii) We have developed improved spectrum management mechanisms, protocols and algorithms to support inter-operator spectrum sharing, licensed shared access, and flexible intra-operator spectrum allocation in the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE)/LTE-Advanced and 5G mobile systems. A number of different use cases have been presented for showing how the COHERENT architecture can support them. Furthermore, COHERENT intends to influence the philosophy behind the next 5G 3GPP system. Therefore, the contribution of COHERENT to the 3GPP framework is also introduced based on COHERENT principles. Finally, SPEED-5G project focuses on hierarchical (blending distributed and centralised) management of ultra-dense multi-RAT and multiband networks in order to investigate the potentials of RRM in each node (distributed).

B. 5G Networks Security and Integrity

The CHARISMA virtualised security solution targets virtualised security in terms of automated security management and virtual security functions (VSFs). The former is being realised with the help of Security Policy Manager and Service Monitoring & Analytics modules, with support from virtualised infrastructure (VI) security and VI monitoring. The latter are implemented as VNFs which can be automatically provisioned through an orchestrator and virtualised infrastructure manager (VIM) in an NFV environment. Starting from additional use cases [30] defined to illuminate 5G Security issues, 5G-ENSURE has advanced 5G Security Vision and initiated a Technical Roadmap [31] on security enablers of major areas of concerns (namely AAA, Privacy, Trust, Security Monitoring and Network management and virtualization) as confirmed by Open Consultation ran publicly on 5G Security in 2016 with support of other projects. Regarding 5G security enablers delivered by 5G-ENSURE they come with open specifications [32] for anyone interest to come up with its own implementation and are obviously 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 [33] (manuals) to integrate/deploy also make use of them within the 5G Security testbed according to use terms and conditions that apply. The 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, the test-bed shows on a small scale what a 5G network could be like.

VII. Virtualization and Service deployment Innovations

This section stresses on the innovations of virtualization and service deployment. The following Golden Nuggets are part of this section:

A. Network Softwarization and Programmability integrating SDN and NFV Technologies

The 5G-XHAUL project [2] works on 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 for the wireless BH. It features Openflow extensions/NETCONF agents 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. Also, 5GEx project has developed the split of Network Function Virtualization Orchestrator (NFVO) into Network Service Orchestrator (NSO) and Resource Orchestrator (RO) for multi-domain interaction. Building on this split of functionality, we have introduced resource Slice as a Service (SlaaS) 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 recently approached a similar NSO-RO functional split for single administration. Furthermore, initial design and deployment of a large scale test-bed (the 5GEx sandbox) connecting 13 sites, including 4 operators providing the connectivity backbone, and emulating realistic Internet topologies today. Additionally, SONATA has developed a flexible NFV MANO Service Platform 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. Superfluidity also elaborates on the fact that complex services can be built through the “chaining” of these Micro-VNFs. Different virtualization approaches can be used to support these micro-VNFs: Tinified VMs and unikernels.

B. E2E Orchestration in Single and Multi-Domains 5G Virtualized Networks

The project 5GEx [11] has broken down the multi-domain orchestration process 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. Moreover, a bottom-up proof of concept prototype of the multi-provider, multi-domain orchestration as an integration of the major concepts from FP7-UNIFY, FP7-T-NOVA, ETICS projects and advanced transport control. In addition, CHARISMA leverages on the open access concept and extends it to network slicing to offer multi-tenancy. That is, it allows infrastructure owners to dynamically share (control, manage, orchestrate) their resources, virtual and physical, in an isolated manner (network slices), among several network operators to offer different customized services to their end customers. This is achieved with the help of an Open Access Manager (OAM) module 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. Also, 5G-NORMA service and domain aware orchestration 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

VirtuWind [28] will develop and demonstrate SDN & NFV ecosystem, based on open, modular and secure framework showcasing a prototype for intra-domain and inter-domain scenarios in real wind parks as a representative use case of industrial networks, and validate the economic viability of the demonstrated solution. The wind park control network has been chosen as a professional application in VirtuWind as wind energy has now established itself as a mainstream of sustainable energy generation. By envisioning lower capital expenditure and operational expenditure costs in control network infrastructure, VirtuWind will play important role in assisting wind energy sector to achieve cost reductions. Further applicability of VirtuWind solution in other industrial domains will bring multifold benefits in their communication networks.

D. Flexible and Agile Service Deployment

The SONATA [13] Service Platform is complemented by the SONATA Service Development Kit (SDK) that aims at fast implementation, testing, and debugging of virtualized network functions and services. To this end, the SDK supports the creation of function and service descriptors as well as service packages which are uploaded to the Service Platform and used to manage the lifecycle of complex network service. Moreover, the SDK 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, say 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. Finally, 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. Moreover, Superfluidity [14] develops a framework to automatically map service level Key Performance Indicators (KPIs) to the platform level parameters in the host compute environment. The framework enables the identification of platform features, which most significantly influence the KPIs for a given workload under test. Full stack monitoring is used to capture a telemetry data ranging from low-level hardware metrics to higher-level applications metrics. The data is analysed using an analytics pipeline which identifies the most significantly correlating platforms metrics with service KPI's, based on the use of eight ranking algorithms with a reliability scoring mechanism. The eight algorithms implemented to date are a mixture of clustering and machine learning classification approaches. In addition, To enforce security in 5G networks Superfluidity takes the following directions; 1) Describe operator policies in a high-level specification language; 2) Describe Reusable Functional Block (RFBs) in a way that is amenable to static analysis through the use of Symbolic Execution Function Language; 3) Perform static analysis of RFB configurations to ensure policy is obbeyed before deployment using SymNet tool (SymNet can run reachability checks over network models by injecting symbolic packets and tracking their path through the network); 4) Ensure that the implementation conforms to the specification at deployment time.

VIII. Conclusions and Way Forward

This paper presented the main Golden Nuggets that derive from the 5G-PPP Phase 1 projects and stressed on the innovations that they bring. These innovations are shared with the global 5G research community in order to avoid fragmentation of standards and deployed technologies. This is being achieved by the 5G-PPP through international cooperation with other regions such as the Americas, China, Japan, Korea. The aforementioned work has set the foundation for 5G-PPP Phase 2 which capitalizes on key outcomes and provides validation of 5G technologies by specifically focusing on verticals (e.g., Automotive, Manufacturing, Energy, Health etc.).

Acknowledgment

This work is supported by the European Commission and 5G Public-Private Partnership as well as the 5G-PPP Phase 1 projects which are presented in this work.

References

[1] 5GPPP, "Innovations for new business opportunities", White Paper, 02/2017
[2] 5G-XHaul website, http://www.5g-xhaul-project.eu/, accessed Feb. 2017
[3] Fantastic-5G deliverable D3.1, "Preliminary results for multi-service support in link solution adaptation", Apr. 2016
[4] Fantastic-5G deliverable D4.1, "Technical results for service specific multi-node/multi-antenna solutions", May 2016
[5] 5G-Crosshaul website, http://5g-crosshaul.eu/, accessed Feb. 2017
[6] X. Costa-Perez et al., "5G-Crosshaul: An SDN/NFV Integrated Fronthaul/Backhaul Transport Network Architecture", IEEE Wireless Communications Magazine, Feb. 2017
[7] X. Li et al., "5G-Crosshaul Network Slicing: Enabling Multi-Tenancy in Mobile Transport Networks", IEEE Communications Magazine, May 2017
[8] Flex5Gware website, http://www.flex5gware.eu/, accessed Feb. 2017
[9] SELFNET website, https://selfnet-5g.eu/, accessed Feb. 2017
[10] CHARISMA website, http://www.charisma5g.eu/, accessed Feb. 2017
[11] 5GEx project website, http://www.5gex.eu/, accessed Feb. 2017
[12] 5G-NORMA website, https://5g-ppp.eu/5g-norma/, accessed Feb. 2017
[13] SONATA website, http://www.sonata-nfv.eu/, accessed Feb. 2017
[14] Superfluidity website, http://superfluidity.eu/, accessed Feb. 2017
[15] mmMAGIC website, https://5g-mmmagic.eu/, accessed Feb. 2017
[16] mmMAGIC deliverable D2.2, "Measurement results and final channel models for mm-wave 5G bands", May 2017
[17] mmMAGIC deliverable D4.2, "Final radio interface concepts and evaluations for mm-wave mobile communications", Jun. 2017
[18] mmMAGIC video, https://youtu.be/-Dxmligo8w4.
[19] mmMAGIC deliverable D1.3, "Visualization of the candidate radio interface concept", Mar. 2017
[20] mmMAGIC deliverable D3.3, "Evaluations of the concepts for the 5G architecture and integration", Jun. 2017
[21] P. Marsch and I. da Silva (ed.) : "5G RAN Architecture and Functional Design" , METIS II white paper, March 2016
[22] METIS-II deliverable D6.1 "Draft asynchronous control functions and overall control plane design", Jun. 2016
[23] METIS-II deliverable D2.2 "Draft overall 5G RAN design", Jun. 2016
[24] "IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond," ITU-R Rec. M.2083, Sep. 2015.
[25] COHERENT deliverable D2.2, "System architecture and abstractions for mobile networks," Jul. 2016
[26] 5G-ENSURE website, http://www.5gensure.eu/, accessed Feb. 2017
[27] SPEED-5G website, https://speed-5g.eu/, accessed Feb. 2017
[28] VirtuWind website, http://www.virtuwind.eu/, accessed Feb. 2017
[29] Zervas, G. S., Triay, J., Amaya, N., Qin, Y., Cervelló-Pastor, C., & Simeonidou, D. (2011). Time Shared Optical Network (TSON): a novel metro architecture for flexible multi-granular services. Optics express, 19(26), B509-B514.
[30] 5G-ENSURE Deliverable D2.1, "Use Cases"
[31] 5G-ENSURE Deliverable D3.5, "5G PPP security enablers technical roadmap (Update)"
[32] 5G-ENSURE Deliverable D3.2, "5G-PPP Security enablers open specifications (v1.0)"
[33] 5G-ENSURE Deliverable D3.4, "5G-PPP Security Enablers Documentation (v1.0)"
[34] METIS II deliverable D3.1 "5G spectrum scenarios, requirements and technical aspects for bands above 6 GHz". May 2016
[35] P. Kyösti, J. Medbo, "A channel model for 5G evaluations", COST-IC1004, January 28-30, 2015, Dublin, Ireland
[36] K. Bakowski, K. Wesolowski, M. Rodziewicz, "Simulation Tools for the Evaluation of Radio Interface Technologies for IMT-Advanced and Beyond", To be published by: CRC Press, Taylor & Francis Group, USA
[37] METIS II deliverable D2.3 "Performance evaluation results", Feb.2017
[38] METIS-II deliverable D5.2 "Final Synchronous Control Functions and Resource Abstraction Considerations," March 2017.