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SPECIAL ISSUE ARTICLE

Flex5Gware: Flexible and efficient hardware and software platforms for 5G network elements and devices

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ABSTRACT

This paper presents the Flex5Gware project, whose goal is to deliver highly reconfigurable hardware (HW) platforms and HW-agnostic software (SW) platforms for 5G network elements and terminal devices. Flex5Gware will enable 5G HW/SW platforms to meet the requirements imposed by the growth in mobile traffic and the diversity of applications by increasing their capacity, reducing their energy footprint and enhancing their scalability and modularity. To put in place this vision in this early stage of 5G PPP research, Flex5Gware is designing and prototyping key building blocks of 5G HW/SW platforms. In particular, the developed technologies will be evaluated and demonstrated with proofs-of-concept by the end of the project. Copyright © 2016 John Wiley & Sons, Ltd.

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1. INTRODUCTION AND MAIN IDEA BEHIND FLEX5GWARE

The mobile data traffic growth is anticipated to reach a 1000 fold increase over the next decade. In addition, this data traffic will support a large diversity of applications ranging from low bit-rate and low power machine-to-machine (M2M) applications to highly interactive and high resolution entertainment applications [1]. Accordingly, to address these challenges, a number of distinct technical requirements on hardware (HW) and software (SW) platforms will have to be reconsidered because these are the platforms on top of which all mobile communication-related functionalities are implemented and executed. Among the most prominent requirements, the following must be highlighted [2, 3]:

- Further improvement of quality of experience (e.g. data rate, capacity, latency and resilience)
- Energy efficiency
- Scalability, modularity and reconfigurability, especially when multiple Radio Access Technologies (RAT) are considered.

To achieve these requirements, highly reconfigurable HW platforms and HW-agnostic SW technologies (targeting both network elements and devices) are needed to enable a smooth transition from 4G mobile wireless systems to 5G.

In particular, Flex5Gware is investigating a number of technical aspects related to HW platforms: analogue HW components for 5G multi-RAT wireless systems, advanced semiconductor technologies and new HW architectures, mixed-signal technologies and conversion stages, digital front-end architectures and flexible HW/SW function partitioning.

Similarly, Flex5Gware is also investigating technical aspects related to SW platforms: modules, functions and interfaces enabled by virtualization technologies, towards a high performance, energy efficient, flexible and reconfigurable, low cost operation and effective service deployment tailored to users' preferences. All these SW-related technologies are being designed with the goal to be HW-agnostic.

Given that the development of 5G is in its early stages, Flex5Gware has adopted an approach where research and implementations are performed on key building blocks of HW/SW platforms and is considering the ability of these building blocks to operate together. This approach entails many design challenges for these building blocks that are being solved through novel technologies as described in the following sections of this paper. However, before delving into the technical content, a brief introduction of the Flex5Gware consortium is given first.

1.1. Flex5Gware consortium

The Flex5Gware consortium counts with partners belonging to all the major players in the mobile networks sector, that is, one mobile network operator (Telecom Italia Mobile), three equipment manufacturers (Ericsson, NEC and Nokia) and two semiconductor chip makers (Intel and Sequans Communications). The consortium also counts with six research centres (CEA-Leti, CTTC, CNIT, Fraunhofer-IAF, iMinds and VTT) and three universities (KU Leuven, Universidad Carlos III de Madrid and Universitá di Pisa) and, finally, it is endowed with two SMEs (TST Sistemas and WINGS ICT Solutions) that are integrating market oriented 5G systems. The geographical origin of the Flex5Gware partners is depicted in Figure 1.

2. FLEX5GWARE VISION

As pointed out in the introduction, among the challenges to be faced by 5G mobile networks, the support of an anticipated 1000 fold mobile traffic increase over the next decade and the efficient handling of many different classes of traffic and services are the two most distinct ones. In response to these challenges, the mobile industry must deliver an economically and energetically sustainable capacity and performance growth strategy; one that offers a superior user experience at lower cost than currently deployed wireless systems.

To achieve these two ambitious goals, a plethora of technological aspects need to be addressed. Among these, the improvement of the performance and the reduction of the energy footprint of the HW and SW platforms are of paramount importance.

It is also worth highlighting that performance improvements require progress not only in quantifiable/quantitative terms (e.g. operated bandwidth or simultaneous computational power enhancement and energy consumption reduction), but also in terms of other important non-functional aspects like scalability, modularity and reconfigurability. This is due to the fact that macro-cellular network capacity cannot continue to increase infinitely. Rather, increasing capacity to keep pace with future demands requires networks that are flatter, more distributed and of heterogeneous nature, and, in general, more scalable and flexible in order to match the cost (resource and energy consumption) with the faced (or anticipated) demand.

Especially in the early stages of the 5G era (2020+), it is expected that devices will have to support multiple

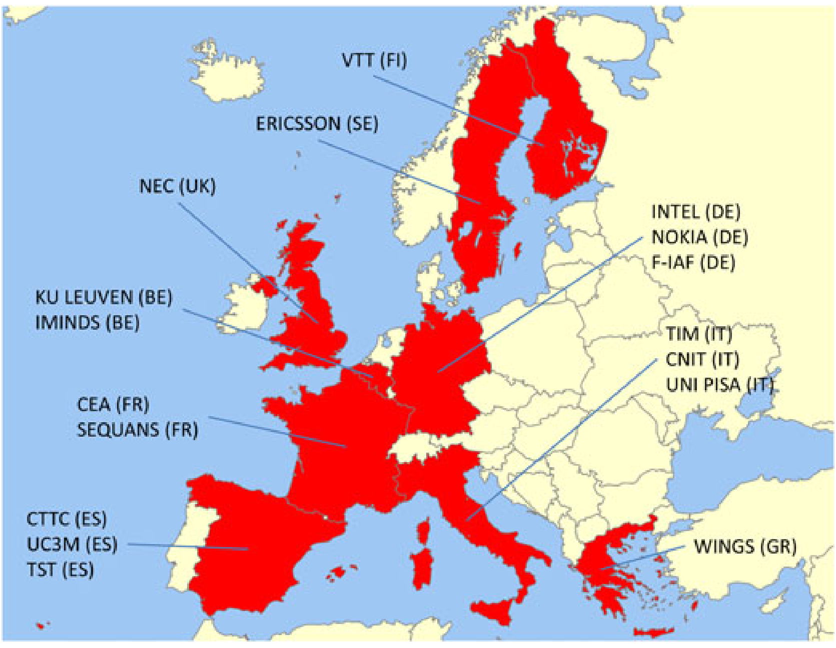

Figure 1. Geographical origin of the Flex5Gware partners.

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RATs and operational modes ranging from device-to-device (D2D) communications to mmWave technologies, and even new body area networks (wearable devices). In later stages of 5G, this multiplicity of RATs is expected to converge into a lower number thanks to the foreseen versatility of the 5G air interface (e.g. GNSS signals might not be needed for all types of terminals due to the good location properties of 5G waveforms, or Bluetooth might be replaced by a short range version of the 5G air interface). All these challenges are calling for a modular design philosophy with flexible HW and SW solutions.

Taking device chipset and platform suppliers as an example, they will face this need to support an increasing number of RATs together with the trend towards a highly diverse set of device form factors, with wearable and machine-type devices joining the almost ubiquitous today tablets and smartphones. This progressive increase in form factor diversity is driving multiple levels of platform support and capability, making transceiver complexity a key challenge for 5G devices. In addition, 5G devices are expected to integrate and interact with a multiplicity of sensors (e.g. those related to location and positioning, environmental conditions, image processing etc.) that will provide context awareness to the communication and the deployed RAT, allowing improvements in the efficiency of existing services, and help to provide new more user-centric and personalised services.

A similar heterogeneous situation to that of 5G devices is also valid for 5G network elements. Because cost and flexibility of deployment will also be important factors, a shift towards SW-based implementations and virtualization technologies will be required. Ideally, these SW-based implementations should be as HW agnostic as possible and, at the same time, supported by versatile, reconfigurable, and flexible HW platforms that are able to cope with all the functionalities needed and invoked from the SW domain. These desirable properties of HW platforms need to be present not only in the analogue and digital domains, but also in the conversion stages (A/D and D/A), which are critical in terms of energy consumption, especially when versatility, reconfigurability and flexibility are required. Additional important challenges in the HW for network elements pertain to performance improvements in terms of, for example, on-chip frequency generation for mmWave bands or active envelope tracking and PA pre-distortion for wideband power amplifiers. Furthermore, the HW has to deal with the addition of new features and capabilities that are not yet in operational use, such as full duplex operation or implementations of massive MIMO technologies, taking into account the additional requirement of increasing the operational bandwidths.

Thus, from all that has been said earlier, the Flex5Gware vision for 5G platforms is that they shall combine legacy mobile broadband concepts, for example, GERAN, HSPA, LTE and new 5G air interface concepts in an efficient manner. The term 'efficient' here refers to implementation complexity and cost aspects, as well as energy and spectral efficiency. In particular, the evolution path of mobile radio specific SW using HW-agnostic APIs to highly reconfigurable HW platforms is a key topic that is currently being studied in Flex5Gware.

In addition, the design of 5G systems can only be based on working assumptions based on today's best knowledge for the anticipated unprecedented growth and performance characteristics of 5G as well as the regulatory conditions. Thus, during this first phase of the 5G PPP projects, rather than proposing a full architecture for the 5G platforms, the Flex5Gware consortium believes that is more beneficial to conduct research and innovation actions on the key building blocks that will enable the versatile, flexible, reconfigurable and efficient operation of HW/SW platforms that will be required in 5G networks. Nonetheless, even if research and demonstration activities in Flex5Gware are being performed on key building blocks, it is always taken into account that these blocks will have to operate together to achieve the desired performance. This requires an approach which is going cross through several disciplines, because the objects of research in Flex5Gware range from low level electromagnetic aspects and analogue HW components (including advanced semiconductor materials), mixed signal technologies and conversion stages, digital signal processing architectures and HW/SW split to more system-wide SW architecture research. The Flex5Gware approach and methodology are described in the next section.

3. FLEX5GWARE APPROACH AND METHODOLOGY

3.1. Approach

The development of the Flex5Gware vision described in the previous section, entails many component and system design challenges that will be addressed through novel technologies. Each technology proposed in Flex5Gware is contributing, at least, to one of the following goals (see Section 4 for more details):

(1) To improve the energy and spectrum efficiency (the latter includes the increase of the operated radio frequency bandwidth via mmWave-band usage and aggregation of spectrum at frequencies below 6 GHz)
(2) To improve the modularity and flexibility (which implies increased reconfigurability and scalability).

The Flex5Gware consortium has identified four groups of technologies that are necessary to reach these goals: RF front-ends and antennas, mixed-signal technologies, digital front-ends and HW/SW function split, and SW modules and functions. For each one of these four technology groups, a list of the most important building blocks is presented as follows:

(1) **RF front-ends and antennas**

   (a) RF subsystems for multiband and reconfigurable operation and maximised total bandwidth operating at radio bands below 6 GHz
   (b) Amplifiers on advanced semiconductor technologies (GaN-on-Si; 28nm CMOS bulk and SOI)
   (c) Active low-cost antennas (compact, conformable) operating below 6 GHz.
   (d) Chip frequency generation in 28 nm CMOS for mmWave bands
   (e) Joint antenna-power amplifier design for mmWave

(2) **Mixed-signal technologies**

   (a) Direct RF signal generation exploiting RF data converters for multiple band operation and large aggregated bandwidth
   (b) Power consumption reduction and linearization techniques based on joint analogue and digital processing (e.g., envelope tracking, predistortion)
   (c) High-bandwidth antenna links based on new fibre-to-the antenna transceiver subsystem technology
   (d) Full duplex operation

(3) **Digital front-end and HW/SW function split**

   (a) Advanced receiver architectures (encompassing flexible and efficient MIMO decoders for user equipments and optimised FEC decoders).
   (b) Flexible HW/SW function split and other architectures providing modularity, scalability, performance improvements and energy efficiency, in full or partial network element virtualization paradigms [4]
   (c) Abstraction of transceiver HW to be supported in 5G programmable terminals (this includes sensor and location awareness integration in the HW)

(4) **SW modules and functions**

   (a) Reconfigurable, reprogrammable SW architecture with appropriate interface abstractions for flexible control and management mechanisms across heterogeneous wireless devices and access networks.
   (b) Feedback-loop analysis/muti-node coordination for 'over the air' real-time operation and update of nodes, targeting reliability, delay and 'safe fail' operation.
   (c) New sets of SW tools consisting of libraries and modules in order to support new SW functions, for example, virtualized base band units (BBU) and reconfigurable layers, offering greater degree of flexibility in terms of configurability.
   (d) Flexible, effective and efficient resource allocation mechanisms.

By the end of the Flex5Gware project, some of these technologies will be directly demonstrated as stand-alone proofs-of-concept (PoC), while some others will be combined to create integrated PoCs. The complete list of Flex5Gware PoCs is provided in Section 5. Figure 2 provides a graphical (and intuitive) representation of the Flex5Gware concept.

3.2. Methodology

The project started in July 2015 with the definition of the scenarios, use cases and general requirements to be fulfilled by the novel 5G communication platforms. Already existing efforts in this field [1, 5, 6] were taken into account and synergies with other ongoing 5G PPP projects were built (such as Metis-II [7], mmMagic [8], Speed-5G [9], or Fantastic-5G [10] to name a few), so as to address a holistic system perspective and maximise the acceptance of Flex5Gware results within the industry community. In this phase, the contribution of the industrial partners of Flex5Gware was essential to align the project scenarios and use cases to the commercial needs of, for example, mobile network operators. The results of this first phase are available in [11].

Next, given the wide scope of the research topics addressed in Flex5Gware, the derived general requirements were particularised for each one of the four technology areas defined in Section 3-A. Accordingly, specific design principles, requirements, and guidelines for the development of the enabling technologies were obtained. These particularisations are especially important in this initial phase of the 5G PPP because they will set the starting point upon which all the technology developments will capitalise. The outcome is available in [12–15].

With these more specific requirements and design guidelines in place, the project execution is now ongoing with the actual technology development. This stage consists of research activities based on theoretical analysis for concept creation, simulation and experimental evaluation of the different proposed technologies and, finally a performance assessment validated in a lab environment.

The final phase of the project flow will be the demonstration, via PoCs, of the developed technologies.

In parallel to all these activities, the technology and exploitation roadmaps for bringing the Flex5Gware solutions to the market is being prepared. In Figure 3, a graphical representation of the Flex5Gware methodology is presented.

Having presented the Flex5Gware vision together with its approach and methodology, the following section will detail and quantise the specific technical objectives of the project.

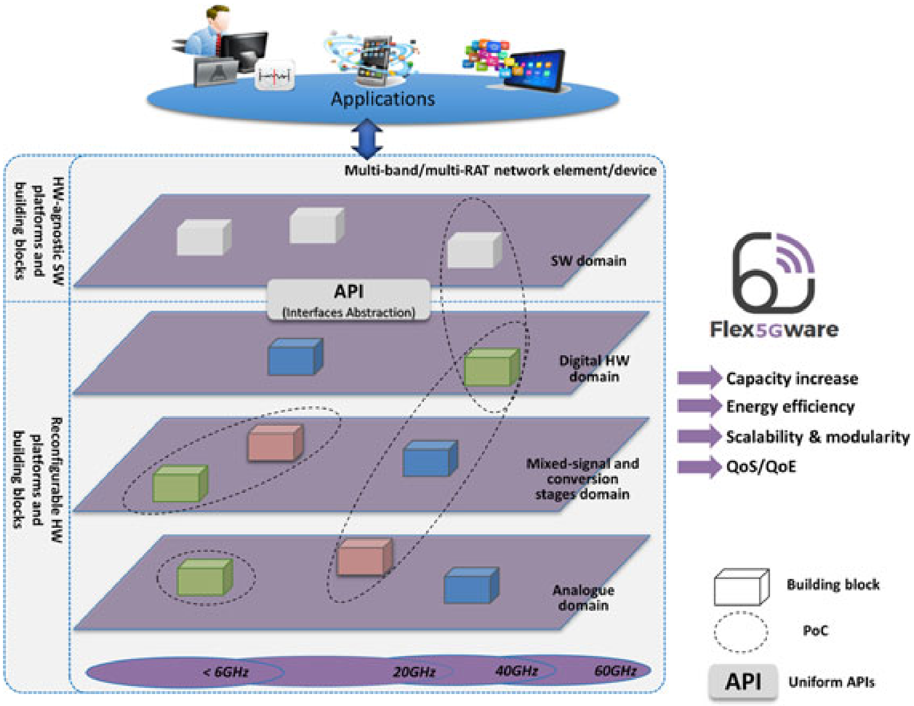

Figure 2. Graphical representation of the Flex5Gware concept. The figure represents the four technology groups as horizontal planes. In each of these groups there are key building blocks, which are represented by the square boxes (coloured boxes represent multiple HW technologies and grey boxes represent HW-agnosticism). The dashed ovals represent Flex5Gware PoCs, either stand-alone (the oval includes only one box) or integrated (the oval contains more than one box).

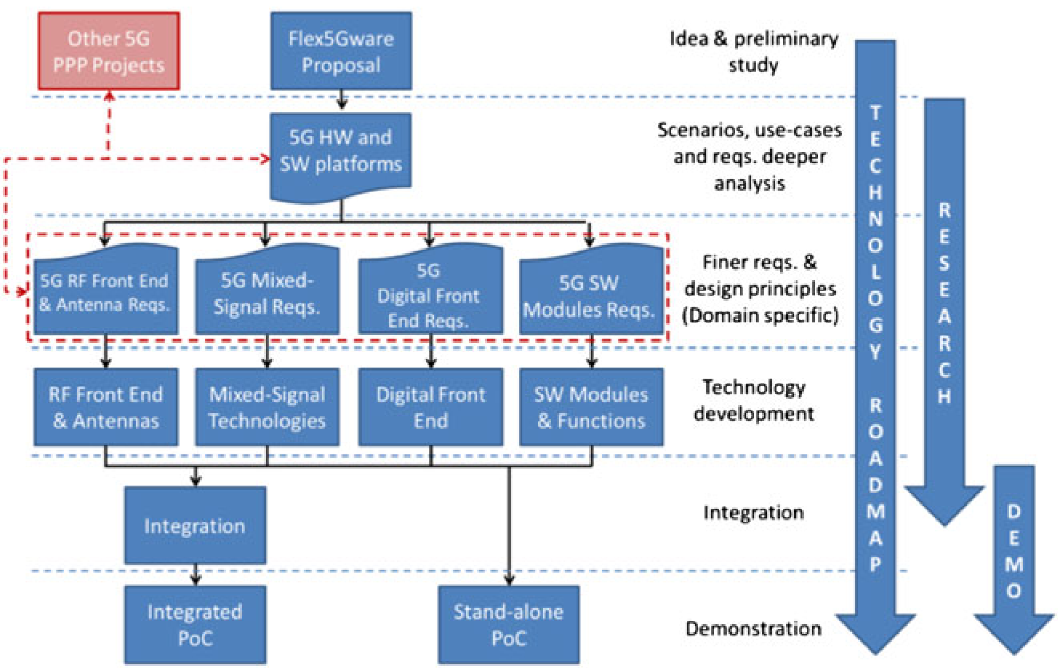

Figure 3. Flowchart representing the Flex5Gware methodology.

4. FLEX5GWARE TECHNICAL OBJECTIVES

In order to fulfil the overall project vision described in the previous sections, Flex5Gware will address the following specific technical objectives:

4.1. Increasing the HW versatility and reconfigurability

Although the SW defined radio (SDR) paradigm and, in general, the digitally assisted analogue front-end have contributed in the direction of increasing the HW versatility and reconfigurability, further improvements will be hard to achieve without novel enhancements on the HW itself. Versatile, reconfigurable and flexible HW components and platforms, which are able to cope with all needed functionalities invoked by the SW domain, are thus required.

More specifically, for systems working below 6 GHz, Flex5Gware is delivering new approaches on versatile multi-band transceiver implementations, together with advanced semiconductor technologies and new HW architectures. By the end of the project, this will result in RF base station key elements (e.g. frequency converters, power amplifiers (PA), and filters) enabling the operation at radio bandwidths (BW) up to 1 GHz and including massive MIMO support.

In the frequency domain above 6 GHz, Flex5Gware is developing RF front-ends (e.g. PAs, low profile antennas) and a low-noise on-chip local oscillator (LO), which will enable the seamless operation of 5G systems at mmWave frequency bands (e.g. the phase noise is expected to be improved by a factor of 10 with respect to current standards like WirelessHD and 802.11ad). Furthermore, regarding the mixed-signal domain, new fibre-to-the-antenna transceiver subsystems for frequencies up to 10 GHz are being developed, which will increase the versatility of base station deployments. Finally, Flex5Gware is dealing with digital signal processing architectures for flexible and modular operation based on HW/SW partitioning techniques of transceiver functions.

All these contributions will lead to increased HW versatility not only in current 4G frequency bands, but also in foreseen 5G bands (including mmWave and unlicensed spectrum).

4.2. Designing and developing HW-agnostic, flexible and cost-effective SW platforms

The control and management of the heterogeneous HW infrastructure and devices expected in 5G is of utmost importance to guarantee an effective service development and deployment, as well as the adaptability to demanding and changing contexts of operation. Thus, scalable, flexible and multi-RAT networks, programmability and dynamic reconfiguration through interface abstractions and uniform application programming ìnterfaces (API) are required, enabling thus a truly HW-agnostic operation.

Flex5Gware is currently specifying the required HW abstractions and SW building blocks in a generic, HW-agnostic and programmable architecture. This will enable the development of services supporting, real-time reconfiguration of the PHY parameters and distributed optimisation schemes based on the orchestration of communication services across multiple nodes. Moreover, HW abstractions also enable to simplify the definition of protocol and control policies, thus decoupling them from specific technologies or manufacturers.

More specifically, the project is defining interface abstractions enhanced by energy awareness offered to the upper layers (e.g. control and management), as well as a generic architecture supporting emerging 5G PHY capabilities (e.g. multiple antennas, dynamic bandwidth, sensing/monitoring operations) and parallel execution of MAC protocols. Flex5Gware is also designing and implementing control and management tools including context extraction and awareness, in order to enable real-time technology-agnostic deployment, composition and reconfiguration of network protocol stacks and SW modules available across multiple nodes thanks to sub-ms level synchronisation schemes. Intelligent, node-level and network-wide decisions on radio and network operation, through a clean separation between data plane and management planes, are also being studied in alignment with the software defined networks (SDN) paradigm, while the impact of the reconfiguration time is also analysed and taken into account in the design of these solutions.

4.3. Increasing the overall achievable capacity provided by 5G communication platforms

As pointed out in the introduction, the anticipated 1000 fold increase in mobile data traffic over the next decade, the massive amount of new applications that networks will have to support, from internet of things (IoT) to Ultra High Definition-TV (UHDTV), as well as the effective service development and deployment tailored to users' preferences, impose the increase of the overall achievable capacity provided by 5G communication platforms.

In the analogue domain, Flex5Gware is providing novel HW solutions designed to support the additional bands in the mmWave range, which are expected to enable the provision of higher mobile data volume per geographical area and higher typical user data rates. In terms of mixed-signal technologies, the following Flex5Gware contributions will increase the achievable capacity of 5G networks: full duplex operation, and direct RF signal generation. In the digital domain, Flex5Gware is studying capacity and user data rate enhancements thanks to, for example, faster LDPC decoding.

Table I. Flex5Gware Proofs-of-Concept.

Innovative proof of concept	TRL
On chip frequency generation	4
Active antennas with integrated power amplifiers for the 20–40 GHz band	4
PAPR reduction and power amplifier predistortion	3
Multiband transmitter	4
Multi-Chain MIMO Transmitter	4
Full duplex FBMC transceiver	3
High-speed low power resilient LDPC decoder	4
HW/SW function split for energy aware communications	4
Reconfigurable and programmable radio platform (terminal side) and SW programming performed and injected by the network	4
Flexible, scalable and reconfigurable small cell platform	4
Flexible resource allocation in CRAN/vRAN platform	4

4.4. Decreasing the overall energy consumed by 5G communication platforms

Communication systems such as Radio Access Networks (RAN) are consuming a significant share of the overall energy consumption [16]. The situation is going to worsen because of the anticipated mobile data traffic increase. The impact will be high in terms of both the environment (due to CO_2 emissions) and operational expenditures (OPEX) as reflected in the cost per delivered bit. To that respect, there is a strong need to increase energy efficiency of communication networks. In Flex5Gware, this is being addressed by the design of different network components and including deployment strategies.

For example, in terms of mixed-signal technologies, Flex5Gware is implementing Peak to Average Power Ratio (PAPR) reduction, predistortion and envelope tracking techniques that can improve the energy efficiency of a base station PA by up to 50% (and up to 30% at the device level).

In the digital domain, Flex5Gware is performing research on, for example, efficient MIMO decoders for user devices (with estimated energy efficiency gains around 20%).

In the SW domain, Flex5Gware will provide novel interfaces, capable to inform the upper layers about the energy/performance trade-offs, and thus enable the best schemes to be selected. The goals are energy efficiency improvements of 15%. Finally, Flex5Gware will provide control and management plane tools and flexible SW solutions for centralized RAN environments that offer energy efficiency through coordination and dynamic reconfiguration, which are clear enablers towards an energy efficient network operation and service deployment. Overall energy savings are expected ranging from 40 to 60% thanks to the activation/deactivation of RRH are expected.

5. FLEX5GWARE PROOF-OF-CONCEPT

As it has been explained previously, in the Flex5Gware project it is of paramount importance to identify and prototype key HW and SW building blocks so that a proof of concept of the Flex5Gware developments can be provided. In particular, performance evaluation activities are essential together with research and development for providing efficient HW and SW solutions and associated platforms for 5G network elements and devices. A fair evaluation can allow the appropriate final system definition and optimisation by means of prototypes, demonstrations and early trials.

Technical research activities carried out in the Flex5Gware project target mainly technology readiness level (TRL) 4, but some activities also target TRL 3.[†]

In the following list, the Flex5Gware PoCs are presented together with their associated TRL (see [17] for more details)

In order to achieve its ambitious objectives put forth in [18], the 5G PPP association envisages a three phase approach [19], which shall bring the researched technologies step by step closer to product applicability. As it has been already discussed previously, Flex5Gware sees its role in phase 1 as performing research on decisive building blocks and concepts as the fundament for further research phases. Nonetheless, Flex5Gware will elaborate a technology and exploitation roadmap for bringing the developed technologies from TRL 3-4 to the market. In addition, the Flex5Gware consortium is already contributing to standardisation activities related to 5G to bring the Flex5Gware developments closer to commercial exploitation. The technology and exploitation roadmap will be publicly available by the end of the project.

Finally, it must be highlighted that the 11 PoCs described in Table I will be showcased together with potential joint demos with other 5G PPP projects in the Flex5Gware final event held at the Telecom Italia mobile and fixed test plant premises in Turin, Italy.

[†]TRL 3: Applied research. First laboratory tests completed. TRL 4: Small scale prototype built and validated in a laboratory environment

6. CONCLUDING REMARKS

Many other research projects within the 5G PPP framework are featuring a top down research approach. As it has been described in this paper, Flex5Gware has chosen a different approach, in pin pointing specific implementation challenges for 5G network elements and devices. The implementation and complexity analysis is used to liaise with other 5G PPP-coordinated projects, to indicate viability of anticipated solutions intended for 5G network elements and devices.

The Flex5Gware collaborative research is aiming as well towards proof of concept implementations whereas the analysis is forward looking to assume the technical enhancements and viabilities of 2020 and the following years.

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REFERENCES

1. European Technology Platform for Communications Networks and Services (NetWorld 2020 ETP), Expert Working Group. 5G Challenges, Research Priorities, and Recommendations. *Joint White Paper*. Available at http://networld2020.eu [accessed on 11 April 2016].
2. Report ITU-R M.2290-0. Future spectrum requirements estimate for terrestrial IMT, December 2013.
3. Andrae ASG, Edler T. On global electricity usage of communication technology: Trends to 2030. *Challenges* 2015; **6**: 117–157. DOI: 10.3390/challe6010117
4. SmallCell Forum. Virtualization for small cells: Overview. Available online http://www.scf.io [accessed on 11 April 2016].
5. Osseiran A, Boccardi F, Braun V, Kusume K, Marsch P, Maternia M, Queseth O, Schellmann M, Schotten H, Taoka H, Tullberg H, Uusitalo MA, Timus B, Fallgren M. Scenarios for the 5G Mobile and Wireless Communications: the Vision of the METIS Project. *IEEE Communications Magazine* 2014; **52**: 26–35.
6. 5G Initiative Team. *5G White Paper by NGMN Alliance,* El Hattachi R, Erfanian J (eds), 2015. Available online: https://www.ngmn.org [accessed on 11 April 2016].
7. Metis-II Project. Available from: https://metis-ii.5g-ppp.eu/ [accessed on 11 April 2016].
8. mmMAGIC Project. Available from: https://5g-mmmagic.eu/ [accessed on 11 April 2016].
9. Speed-5G Project. Available from: https://speed-5g.eu/ [accessed on 11 April 2016].
10. Fantastic-5G Project. Available from: http://fantastic5g.eu/ [accessed on 11 April 2016].
11. Deliverable D1.1 “5G system use cases, scenarios, and requirements break-down” H2020-ICT-2014-2-671563 Flex5Gware project. Available at: www.flex5gware.eu [accessed on 11 April 2016].
12. Deliverable D2.1 “Requirements and concepts for the analogue HW in 5G mobile systems” H2020-ICT-2014-2-671563 Flex5Gware project. Available at: www.flex5gware.eu [accessed on 11 April 2016].
13. Deliverable D3.1 “Mixed-signal strategies for 5G: requirements and concepts” H2020-ICT-2014-2-671563 Flex5Gware project. Available at: www.flex5gware.eu [accessed on 11 April 2016].
14. Deliverable D4.1 “Requirements and concepts for the digital HW in 5G transceivers” H2020-ICT-2014-2-671563 Flex5Gware project. Available at: www.flex5gware.eu [accessed on 11 April 2016].
15. Deliverable D5.1 “System level architecture specification” H2020-ICT-2014-2-671563 Flex5Gware project. Available at: www.flex5gware.eu [accessed on 11 April 2016].
16. Deliverable D2.3, “Energy efficiency analysis of the reference systems, areas of improvements and target breakdown,” INFSO-ICT-247733 EARTH D2.3.
17. Deliverable D6.1 “Preliminary PoC evaluation in Flex5Gware” H2020-ICT-2014-2-671563 Flex5Gware project. Available at: www.flex5gware.eu [accessed on 11 April 2016].
18. EU Commission and 5G PPP contract. Available at: https://5g-ppp.eu/contract/. The technical annex is also available at https://5g-ppp.eu/wp-content/uploads/2014/02/Advanced-5G-Network-Infrastructure-PPP-in-H2020FinalNovember-2013.pdf [accessed on 11 April 2016].
19. 5G PPP website https://5g-ppp.eu/ppp/ [accessed on 11 April 2016].