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Design Methodology for 6G End-to-End System: Hexa-X-II Perspective

SYLVAINE KERBOEUF[1] (Member, IEEE), PAWANI PORAMBAGE[2], (Senior Member, IEEE), AKSHAY JAIN[3] (Member, IEEE), PATRIK RUGELAND[4], GUSTAV WIKSTRÖM[4], MÅRTEN ERICSON[4], DINH THAI BUI[1] (Member, IEEE), ABDELKADER OUTTAGARTS[1] (Senior Member, IEEE), HEIKKI KARVONEN[5], POL ALEMANY[6], RAUL MUÑOZ[6] (Senior Member, IEEE), RICARD VILALTA[6] (Senior Member, IEEE),, PANAGIOTIS BOTSINIS[7], AURORA RAMOS[8], JOSUE CASTANEDA CISNEROS[4], MEHMET KARACA[9], CHRISTINA KAROUSATOU[10], SOKRATIS BARMPOUNAKIS[10], PANAGIOTIS DEMESTICHAS[10], ANASTASIOS ZAFEIROPOULOS[11] (Member, IEEE), IOANNIS TZANETTIS[11], SYMEON PAPAVASSILIOU[11] (Senior Member, IEEE), PIETRO G. GIARDINA[12], GIADA LANDI[12], BIN HAN[13] (Senior Member, IEEE), AHMAD NIMR[14], (Member, IEEE), AND MIKKO A. UUSITALO[3] (Senior Member, IEEE)

[1]Nokia Bell Labs, Nokia Networks France, 91300 Massy, France

[2]VTT Technical Research Centre of Finland, 02044 Espoo, Finland

[3]Nokia Bell Labs, 02610 Espoo, Finland

[4]Ericsson Research, 164 83 Stockholm, Sweden

[5]Siemens Industry Software Oy, Siemens EDA, 90570 Oulu, Finland

[6]Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA), 08860 Barcelona, Spain

[7]Apple Technology Engineering, 80335 Munich, Germany

[8]ATOS-EVIDEN, Madrid 34467, Spain

[9]Ericsson Research, Istanbul, Turkey

[10]WINGS ICT Solutions, 171 21 Athens, Greece

[11]Institute of Communication and Computer Systems, 157 73 Athens, Greece

[12]Research & Development, Nextworks, 56122 Pisa, Italy

[13]Division of Wireless Communications and Radio Positioning (WICON), University of Kaiserslautern (RPTU), 67663 Kaiserslautern, Germany

[14]Vodafone Chair for Mobile Communications Systems, Technische Universität Dresden, 01062 Dresden, Germany

CORRESPONDING AUTHOR: P. PORAMBAGE (e-mail: pawani.porambage@vtt.fi)

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ABSTRACT As the fifth generation (5G) mobile communication systems are commercially deployed, they bring new services, enhance user experiences, and offer various opportunities to different industries. Despite its advancements, 5G encounters several challenges. To tackle these issues, global industrial, academic, and standards organizations are actively researching on sixth generation (6G) wireless communication systems. 6G networks are envisioned as a transformative shift in the interactions between the physical, digital, and human realms, paving the way for a pervasive human-centered cyber-physical world. 6G is positioned to be a platform that offers communication and beyond communication services considering both performance and value centric technological development approaches. In this paper, we present the way forward towards the design of 6G end-to-end (E2E) system as a consolidated view of leading industry stakeholders and academia in the European level 6G flagship project Hexa-X-II. We discuss the key challenges with 5G and how 6G is expected to tackle those by introducing new technological innovations and supporting novel use case requirements. We provide a comprehensive methodology for the design of a 6G E2E system including ten principles, a blueprint, and a structured design process. The architecture design principles prioritize environmental sustainability, digital inclusiveness, and trustworthiness, considering their impact on the 6G E2E system. The blueprint is described corresponding to the infrastructure, network centric application, and application layers, as well as the pervasive functionalities and the relevant technological innovations. Following the design principles and the system blueprint, the design process is demonstrated as two-way approaches (i.e., 1) key performance and value indicators based design process. 2) top-down versus bottom-up alignment process) through the lens of a collaborative robot use case. Through this use case, a special attention is given to the technological enablers that cover management and orchestration functionalities and their 6G enhancement to go beyond the limitations characterizing the previous network generation. In addition, virtual modelling aspects related to digital twining and simulations for 6G E2E system design are also discussed.

INDEX TERMS 6G, end-to-end, platform, system, blueprint, network architecture, design process, use case, key value indicators, key performance indicators, collaborative robots.

I. INTRODUCTION

THE VISION of the sixth generation (6G) of mobile networks is framed as the interaction between the physical, digital, and human worlds which will be powered by the advancement of information, communication, and computation technologies towards a pervasive human centered cyber-physical world in 2030 [1], [2]. It is foreseen that 6G will unleash new businesses by offering novel digital services that will transform communications in the next decade. As a pre-requisite to meet the needs of the business and societal transformation in this vision, 6G will introduce a paradigm shift from the former generations' (G's) "built for performance" to a new paradigm of "built for values and performance". This implies that future networks should consider not only the conventional and potentially novel Key Performance Indicators (KPIs), but also prioritize Key Value Indicators (KVIs) [3], [4]. As such, the key values should be assessed with respect to the outcome on economic, social, and ecological values associated with measurable metrics and adopted in the network design of 6G.

In the context of values-driven research and development activities towards 6G, it is vital to give due attention to societal goals such as sustainability, digital inclusion, and trustworthiness [5]. Environmental as well as economical sustainability are design priorities for the 6G end-to-end (E2E) system, leading to a focus on resource efficiency, notably in energy consumption. Social sustainability is also considered through trustworthiness and digital inclusion [6], [7]. Trustworthiness needs to be wider in the 6G era to address concerns that may arise from the expansion of technologies such as joint communications and sensing (JCAS) and pervasive use of artificial intelligence (AI)/ machine learning (ML) driven network operations [7]. Digital inclusion includes not only providing access to users to 6G networks and devices in remote areas that lack access to digital services due to geographical and economic reasons but also ensuring that individuals and communities have the digital skills necessary to use the new technologies effectively.

To reach the aforementioned vision, 6G is expected to provide a wider range of services that not only go beyond the typical communication services to users and applications, but also provide both performance and value [3]. Hence, the 6G platform view can be expressed as a set of technologies and interfaces that will deliver the future 6G services to applications, ecosystems, verticals, and end users, enabling values (i.e., in terms of economic, societal, and environmental values for different stakeholders). Concretely, the 6G platform will not only provide connectivity and deliver data, but it will process data, generate insights, and deliver additional valuable services such as compute services to applications in need of data processing, storage, and management, intelligent services (e.g., such as AI functionality, analysis, and optimizations). These services can also include spatial/temporal data services such as awareness and localization of objects and surroundings, mapping, and synchronization. Additionally, close collaboration between a significantly wider ecosystem as compared to the previous G's, including but not limited to mobile network operators, cloud providers, vertical industries, integrators, application developers, application service providers and end users, will be a prerequisite to create value for all the ecosystem players and society at large. Moreover, all the ecosystem players expect support for different use cases and services, which can hence benefit from a platform that can be tailored to their specific needs. With this background, the main objectives and the contributions of the ensuing study are presented next.

A. PAPER OBJECTIVE

Since the first research paper on 6G vision was published in 2018 [8], a plethora of articles have been published on 6G research, including review articles and comprehensive surveys covering 6G vision, disruptive technologies, use cases, and roadmaps for development [9], [10]. The 6G vision is often presented in terms of novel applications [11], technological trends in communication [12], networking, and computing, as well as architectural changes associated with 6G networks [13]. These discussions address open research questions and challenges in the evolution of 6G, exploring potential technologies for spectrum [14], networking, air interface, architecture [15] and other paradigms such as blockchain [16], edge intelligence [17], quantum machine learning [18] or digital twin [19]. Numerous review compilations also delve into security, privacy, and resilience issues in 6G [20]. These discussions cover topics such as quantum-safe communication, security automation, AI/ML-assisted intelligent and energy-efficient security and privacy solutions, and trust management mechanisms [21], [22]. The findings from these research outcomes are originated from various 6G initiatives worldwide (i.e., some are outlined in Section II-C), contributing to advancements in 6G research, encompassing definition, specification, standardization, and regulation [2].

While various research projects and literature have explored the vision and potential of 6G, there is still a need for a comprehensive and well-structured methodology for designing 6G E2E system with a broader perspective. This is primarily because, unlike previous generations of mobile networks, 6G is designed not only with a focus on performance indicators but also considering societal values and sustainability aspects. The process of designing 6G E2E system needs to target achieving the essential 6G objectives, such as sustainability, inclusiveness, and trustworthiness. Moreover, the process needs to be supplemented by the lessons learnt from the mistakes identified in previous generations 4G and 5G. Consequently, to contribute to this journey of driving 6G vision towards a reality, the European 6G flagship project Hexa-X-II [23] aims to delve into the details of the design process of 6G E2E system that meets the needs and expectations with respect to hardware, software, and applications vis-à-vis 6G [24], [25]. In this paper, we share a consolidated view about the design methodology of 6G E2E system from a broader research community involved in Hexa-X-II project. This endeavor encompasses a wide spectrum of insights, visionaries, and skills drawn from both academic and industry communities.

B. PAPER CONTRIBUTION

Given the objective of presenting the methodology for 6G E2E system design process in the Hexa-X-II project, the following are the key contributions we provide in this paper to enlighten the 6G research and scientific community.

1. The paper explores the primary motivations behind the transition from 5G to 6G, identifies prominent 6G use case families, and aligns their requirements with the 6G E2E system. It also presents the view of 6G as a platform supporting innovative services.
2. Another key contribution in the paper is to explain the ten architecture design principles and their impact on the blueprint of the 6G E2E system.
3. Next, the paper presents a blueprint for the 6G E2E system, outlining its components, functionalities, and distinctions from the architectures of 4G and 5G.
4. The paper presents a novel 6G E2E system design process as two iterative approaches: KPI/KVI-based design processes and top-down vs. bottom-up alignment processes.
5. To exemplify the design process, the paper demonstrates the design lifecycle of the 6G E2E system using a collaborative robot use case particularly for a selected set of technological enablers that cover management and orchestration functionalities.
6. The paper also provides a demonstration of virtual modeling particularly for Radio Access Network (RAN) modelling as a part of the E2E simulation framework.

The remainder of the paper is organized as follows: Section II provides the motivation for the 6G E2E system that includes the evolution from 5G to 6G, some insights about system requirements and the 6G platform view. Section III describes ten architecture design principles and their impact on the 6G E2E system. Section IV presents a blueprint for 6G E2E system with the details of its components. Section V describes the design process of the 6G E2E system that is presented based on two approaches (i.e., KVI/KPI based approach and top-down versus bottom-up approach). Section VI demonstrates the design process of the 6G E2E system by considering a collaborative robot (cobot) use case as an example. Section VII discusses potential advantages of virtual modeling and introduces the 6G E2E simulation platform. Finally, in Section VIII conclusions are provided.

II. MOTIVATION FOR 6G END-TO-END (E2E) SYSTEM

Starting from the evolution from 5G to 6G, this section describes the key requirements for the development of a 6G E2E system, and the novel 6G services that can be offered by a 6G platform.

A. EVOLUTION TOWARDS 6G END-TO-END SYSTEM

Each of the previous generations (G's) has been built upon performance-based requirements given the fast-paced evolution of applications and their corresponding requirements from networks, be it wireless or wired. Additionally, to ensure a smooth and long-term serviceability of the infrastructure and existing services, the telecom ecosystem spearheaded by 3rd Generation Partnership Project (3GPP), has developed viable migration solutions [26].

Consequently, one of the lessons learnt from the previous generational shift, i.e., from 4G to 5G, is to limit the number of deployment options [27]. This is because, the development of 5G, which was initially focused on the non-standalone (NSA) option, delayed the rollout of the much more capable and powerful standalone (SA) option, supporting e.g., network slicing and ultra-reliable low latency communication (URLLC). Concretely, in 5G NSA the 5G radio access technology (RAT) New Radio (NR) was provided as a booster while the main connectivity remained on the 4G RAT E-UTRA (Evolved Universal Terrestrial Radio Access). For the core network (CN), the connection remained in the 4G Evolved Packet Core (EPC). It was only when the NSA was developed and deployed that work on 5G SA began in earnest, delaying the deployment of the connection to the 5G core network (5GC). Since there were two alternatives for the RAT, and two alternatives for the CN, all different combinations and permutations were developed and standardized, which further delayed the development and

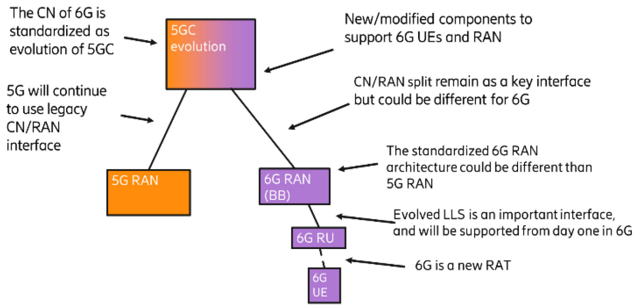

FIGURE 1. 6G RAN connected to an evolved 5GC [24].

deployment of 5G SA. In the end, only the 5G NSA with E-UTRA and NR connected to EPC, and the 5G SA have been deployed.

Hence, for 6G, these large number of deployment options should be avoided, so that the research and development can focus on 6G SA from the beginning [28]. To achieve this, the development of the 6G CN should be done as an enhancement of the 5GC so that both 5G RAT and 6G RAT can connect to the same CN from the start as can be seen in Figure 1.

5G also introduced a split in the RAN, called the higher layer split, i.e., between the Packed Data Convergence Protocol (PDCP) and Radio Link Controller (RLC) layer in the protocol stack, and standardized a multi-vendor interface called F1 between them. The motivation used was that the Radio Resource Contol (RRC) and PDCP layers handled slow-warying configurations that could be placed further away in a central unit (CU) compared to the RLC, Medium Access Control (MAC), and physical (PHY) layer that were placed in a distributed unit (DU) closer to the user equipment (UE). However, when 5G was deployed, it was realized that the RRC in the CU needed information on the cells and carriers collected by the RLC, MAC and PHY, in order to properly configure the UE with RRC configurations. Thus, the F1 interface became a bottleneck for efficient and timely configurations of the UEs [29]. In 6G, the RAN should rather be split at a lower layer, e.g., parts of the PHY layer are distributed to Radio Units (RU) while the rest of the protocol stack are executed in a baseband unit (BB).

Furthermore, 5G, as inherited from 4G, has in several instances implemented redundant solutions to handle the same problem, with comparable performance. For instance, there are two different methods to perform inter-cell handover, namely vertically through the CN via the N2 interface, or horizontally in the RAN via the Xn interface. The performance of these two solutions only depends on the deployment of the backhaul, i.e., neither is inherently superior. However, since the Xn interface is not always available, and the N2 handover sometimes is the only option (e.g., when changing Access and Management Function (AMF) node), the Xn handover solution evince to be a superfluous solution. Similarly, there exists two separate solutions to aggregate data from multiple carriers, namely carrier aggregation (CA) and dual connectivity (DC). The difference lies in where the data is aggregated, (in the MAC layer for CA and in the PDCP layer for DC) and where the resource control lies (in a single RRC entity in one node for CA and split into two separate RRC entities in different nodes). The main nominal difference between CA and DC is that DC can allow larger latencies between the carriers. However, in practice if the latency is too large the data flow control between the nodes becomes either too large or too small, preventing full utilization of the resources [30]. If the latency is small, the performance of CA and DC becomes comparable.

In addition, several features were introduced late in 5G, resulting in suboptimal implementations that need to align to the existing functionality. For instance, non-terrestrial networks (NTN), low performance devices (e.g., narrowband Internet of Things (NB-IoT) and implementation of AI and other beyond communication services (e.g., JCAS) can gain from significant improvements. In 6G, these concepts should be incorporated from the beginning to fully incorporate the functionality.

Furthermore, to provide a smooth, gradual deployment of 6G, efficient spectrum sharing techniques should be implemented in 6G from the first release. This will allow operators to deploy a 6G RAT in an area with existing but underutilized 5G RAT and spectrum and to dynamically redistribute the spectra between 5G and 6G as needed. In Table 1 we provide a summary of the main challenges with 5G and how they are expected to be tackled in 6G

B. USE CASE REQUIREMENTS FOR 6G E2E SYSTEM

There has been significant work in the past couple of years, trying to define the potential use cases for 6G. e.g., the Finnish 6GFlagship released a whitepaper in September 2019 [31], the European 6G flagship project Hexa-X released a first set of use cases in February 2021 [32] which were built upon the existing 5G use cases, and the visions from the contributing partners. Many different companies and organizations have released their own take at the 6G use cases, e.g., the Chinese IMT-2030 promotion group in July 2021 [33], the operator consortium NGMN in February 2022 [34], the North American Next G Alliance in June 2022 [35], the Indian TSDSI in October 2022 [36], the Japanese Beyond 5G Promotion Consortium in March 2023 [37] and recently ITU-R approved the Framework and overall objectives of the future development of IMT for 2030 and beyond, which outlines a number of usage scenarios that will define 6G [38]. In addition, Hexa-X-II released an updated set of use cases in December 2023 [39].

Although the details of the use cases as well as the grouping and highlighted features, proposed by the various initiatives vary, the broad strokes and overall principles remain remarkably consistent as can be seen in Figure 2, where the use cases are grouped related to the ITU-R usage scenarios. Most initiatives discuss some form of integration of AI, immersive communication, Machine-type

TABLE 1. A summary of main challenges with 5G and how 6G design is expected to tackle them.

Challenges with 5G	How 6G is expected to tackle the challenges
5G was not designed for AI services or internal AI functionality.	A 6G architecture should inhertently support AIaaS both in-network use and for external use to improve the injection of automation and distributed intelligence characteristics.
Sensing is not standardized in 5G.	Sensing will be integrated as a fundamental capability in 6G. Furthermore, JCAS characteristics will be supported, considering the seamless fusion of advanced sensor technologies with ultra-fast wireless networks, enabling real-time data collection and transmission for diverse applications needs.
Positioning focused on basic localization-based services with moderate precision.	6G positioning will be significantly enhanced for enabling highly precise location-based services.
There is no standardized method for device compute offloading	6G will support methods for device compute offloading by extending existing compute offloading techniques for edge/cloud infrastructures e.g., offloading video rendering in lightweight XR devices.
Integration of NTN was introduced as add-on in 5G.	Design 6G system from beginning to incorporate NTN solutions to enable support from the devices and the possibility to optimize the performance also for the NTN services.
5G management and orchestration framework need to be improved to support both the 5G services as well as the new 6G services and use cases.	To enable the new services in 6G from the beginning a management and orchestration framework should be designed to provide programmability, flexibility, scalability, and reliability. This management and orchestration framework moves beyond the strict limits of a network provider and considers interaction with multiple tenants and Over the Top (OTT) players.
Since 5G was designed focusing on performance-based requirements it was unable to accommodate new value requirements coming from novel use cases.	Design 6G not only focusing on performance-based requirements, but also with the value-based requirements for the societal, environmental and economical.
Complex interworking between 4G and 5G, and the use of NSA	Build 6G CN as an extension of 5GC and focus on 6G SA as the only option.
Two kinds of aggregating multiple carriers (CA and DC) with comparable performance.	Develop a single multi-connectivity solution for data aggregation to avoid market fragmentation.
Higher layer split (F1 interface) divides resource allocation in two parts causing worse	Ensure a single RAN control function to control the UE's radio resource at any point in time.
control signaling decisions, delayed actions and increased processing load.	

communication with the different use case scenarios. In this paper, we will focus on the Hexa-X-II use cases [39], however as can be seen in Figure 2, this mapping is quiete well aligned with the global consensus on use cases. In particular, a specific application of the Collaborative Robots use case will be further elaborated in Section VI. Table 2 outlines some of the most important requirements for the Hexa-X-II use cases [39] as well as the relevant 6G functionalities needed to fulfill the requirements. The requirements for 6G E2E system are closely correlated with these 6G use cases as well as the performance and values they incur. Typically, to build any system, it is foremost essential to understand the technical requirements of the system to facilitate the respective use cases. The technical performance requirements define the qualities or characteristics that describe how the 6G network should perform. For instance, as adapted from the ITU IMT-2030 guidelines [33] the technical requirements of the radio design of 6G are defined with respect to peak data rate, latency, mobility, area traffic capacity, user experience data rate, peak spectral efficiency, connection density, reliability, positioning and sensing, global coverage (for digital inclusion), energy efficiency, security, privacy and resilience, and other sustainability aspects (e.g., materials) in its requirements palette. Owing to the recent rise in interest for positioning and localization using cellular networks by industry verticals, IMT-2030 now specifies a 1-10 cm positioning requirement. On the other hand, IMT-2020 does not specify any positioning accuracy requirements. However, for the rest of the new capabilities (e.g., sensing, AI, compute), the quantification of these requirements has not been provided with the quantified figures.

C. 6G PLATFORM VIEW FOR NEW 6G SERVICES

As stated above 6G is not only to provide communication services but also to provide other capabilities and digital services which are beyond communication. With that, 6G platform is presented as the external view of a set of technologies and interfaces delivering 6G services to applications, ecosystems, verticals, users, with the goal of eabling values to the society, economy and environment.

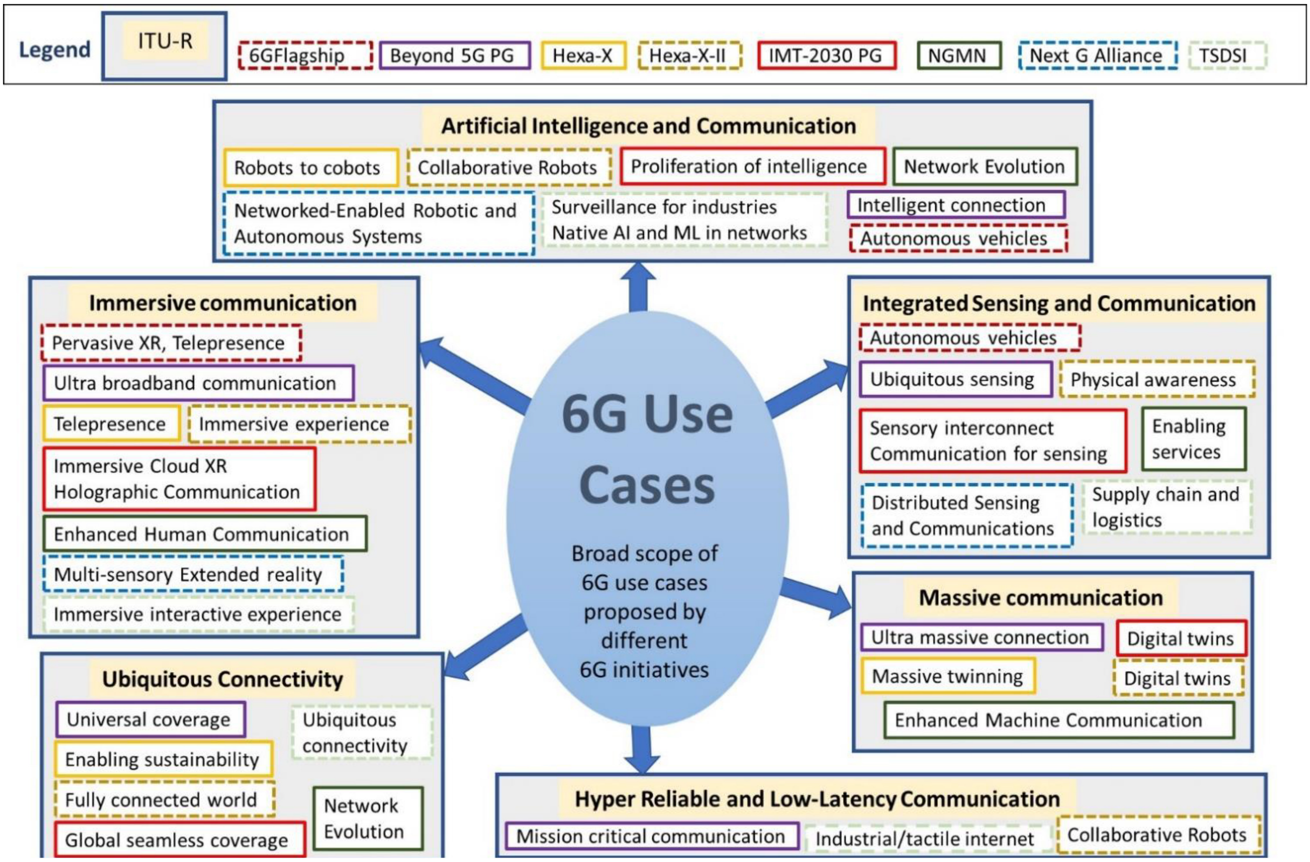

FIGURE 2. Clustering of 6G use cases proposed by various initiatives.

6G as a platform necessitates a perspective that considers external factors, influences, or end-user requirements when shaping up the design process and functionalities. Compared to the previous generations of mobile networks (e.g., 4G and 5G), 6G emphasizes a user-centric and holistic approach to system design, taking into account the broader ecosystem in which the 6G system will operate [10]. Instead of starting the design process solely from an internal or technical standpoint, this type of an outside-in approach involves understanding and incorporating insights from the external environment, such as user requirements, market trends, societal needs, sustainability aspects and other factors that impact the system's usability and effectiveness. This approach aims to create a system that aligns closely with the real-world needs and expectations of users and stakeholders, fostering a more adaptive and responsive design.

In 5G, the network is capable of exposing a set of services through application programming interfaces (APIs) directly to applications, users and verticals, which can be extended over time. However, while these capabilities are already feasible within the framework of 5G, they are currently utilized to a limited extent. Extending this capability further on the 6G platform, a broader range of services are offered from communication functionality to management and orchestration services for applications and networks. Novel and well-defined APIs are required to expose such capabilities from the 6G platform. With that, the 6G platform will not only transport data at best effort, but provide application-level differentiation through performance guarantees and also go beyond communication to process and store data (e.g., auxiliary services such as device compute offload) and being the source of data themselves (e.g., information services such as localization and mapping).

III. ARCHITECTURE DESIGN PRINCIPLES FOR 6G END-TO-END SYSTEM

This section introduces ten principles for the architecture design of the 6G E2E system. Moreover, it provides a comprehensive analysis of mapping those principles with the impact on different component design of the E2E system.

A. ARCHITECTURE DESIGN PRINCIPLES

In order to guide the design process of the 6G E2E system, the Hexa-X-II project has stipulated a number of design principles, intended to capture the most pertinent aspects that need to be addressed [24]. It is worth noting that some of these principles has been considered in 5G and continue to be relevant for 6G. These principles are briefly introduced below and their mapping with the 6G E2E system design is presented in Table 3:

TABLE 2. An overview of requirements and functionalities for the Hexa-X-II use cases.

Use case and requirements	Functionalities provided by the network (reinforced by 6G)
Collaborative robots High data rates Local connectivity Reliability and low latency Sensing Localization Integrated intelligence	The collaborative robot use case envisions autonomous robots cooperating with each other and with humans to solve specific tasks.As cobots are likely to be operating in confined areas, the higher frequencies at mmWave and sub-THz are viable options to provide the connectivity and also support flexible topologies. As the robots need to move around, they will need to sense and navigate in the surrounding, where JCAS as a key 6G functionality could come in handy. To minimize the onboard power consumption, dynamic compute offloading and AI-as-a-Service would move some of the processing to the network.
Immersive experience High data rate with bounded latency Low power consumption devices	The immersive experience use case is the natural progression of the 5G XR use case, where more lightweight devices can provide mobile XR services. and the compute offloading can reduce the power consumption of the resource constrained devices. The continued development of mmWave and sub-THz can provide the necessary bandwidth to support the use case.
Physical awareness High data rates Low power consumption devices Localization Sensing	The 6G system is envisioned to be a network platform, providing not only connectivity, but also expose data and services that go beyond connectivity. One such aspect is the sensing information it can collect, either through JCAS, or through traditional sensors. This will enable the network to provide a physical awareness, with data shared where needed. To analyze the sensing data, the network will have to employ AI/ML models to be able to update it in real-time.
Digital Twins Low E2E latency Full coverage Sensing	Digital twinning was introduced in 5G, and entails creating a digital representation of relevant aspects of a physical entity, system, or process. To be able to monitor, control, and predict the behaviour of the physical system, the digital twin need to be continuously updated with information from the physical system provided by local sensor system through JCAS. This will require efficient connectivity, allowing flexible topologies to assure the full coverage. To process the data from the digital twin, local compute offloading and flexible AI/ML functionality would be required.
Fully connected world Full coverage Flexibility Low power consumption devices	To achieve global area and population coverage, 6G will need to incorporate non-terrestrial networks, as well as flexible topologies that can dynamically provide coverage where needed. In addition, the devices will also need to be available, where cheap energy-neutral devices, that doesn't require battery charging or replacement, can enable more widespread connectivity.
Trusted environments Reliability Low power consumption devices	For local connectivity, e.g., in a factory or on-body network, the reliability of the connectivity and privacy of the data. To achieve this, it will be important to provide efficient connectivity, with the possibility to flexibly extend the network topology where needed. To facilitate integration of resource-constrained devices, compute offloading would be required.

1. *Support and exposure of 6G services and capabilities:* In addition to supporting legacy (e.g., enhanced Mobile Broadband (eMBB) and voice) and novel services (e.g., sensing, AI, or computational related) and use cases as described in section III-B, the 6G platform should be designed to offer access to capabilities and services to allow customization and bundling suited for specific needs.
2. *Full automation and optimization:* The 6G system should fully leverage on the advances in AI/ML to support automation and optimization where it is suitable.
3. *Flexibility to different network scenarios:* To support all current and envisioned future use cases, it will be crucial to incorporate many different modalities of connectivity, including wide-area macro networks, local pico-networks, terrestrial and non-terrestrial networks (NTN) and public and non-public networks (NPN) with a network architecture that supports seamless mobility between them.
4. *Scalability:* To enable a quick and smooth deployment of the 6G networks, it will be important to enable a gradual expansion of the network, to be able to extend it as needed. Similarly, the networks should be designed to be able to scale down (e.g., temporarily) when the needs subside. Scalability of the computational resources used for the provision of network services and applications has also to be supported.
5. *Resilience and availability:* With the widespread proliferation of mobile devices and applications permeating our societies, it becomes more and more critical that the services are available wherever and whenever needed, even in the event of unforeseen disruptions. The 6G design needs to incorporate options for extended coverage, enhanced redundancy and recovery mechanisms.

TABLE 3. Mapping of architecture design principles and their impact of 6G E2E system design.

Architecture design principle	Impact on 6G E2E system blueprint design	Key values
1. Support and exposure of 6G services and capabilities	This feature encompasses generic and dynamic exposure functionalities, e.g. simplified APIs to expose capabilities to E2E applications facilitating seamless integration of beyond communication network functions and hardware capabilities. It emphasizes the inclusion of pervasive AI and a robust compute infrastructure to enhance the overall flexibility for compute offloading of services and improve the performance of the system.	Sustainability, Trustworthiness, Inclusiveness
2. Full automation and optimization	The 6G E2E system requires to establish a comprehensive and widespread data and analysis framework, complemented by a pervasive AI framework and pervasive service management and orchestration. The emphasis is on building a pervasive infrastructure that enables efficient data handling, robust AI integration, and seamless service orchestration across diverse scenarios.The pervasive AI framework provides means for predictive orchestration, distributed AI/ML agents to optimize the system without human interaction.	Sustainability, Trustworthiness
3. Flexibility to different network scenarios	This design principle is for establishing a pervasive service management and orchestration framework. It also involves exposing the infrastructure to the network layer for transparent access, incorporating Gateway UEs, implementing programmable transport configurations and having application awareness and adaptive quality of service (QoS) and quality of experience (QoE).	Sustainability, Inclusiveness
4. Scalability	This focuses on creating a pervasive service management and orchestration system (e.g., scaling up and down based on mobility and time-varying traffic needs), incorporating a network-centric exposure layer and optimized transport network functions (e.g., over heterogeneous multi-domain/multi-clouds). In addition, network modularity will enable dynamic and efficient introduction and removal of network resources as needed.	Sustainability, Trustworthiness
5. Resilience and availability	The 6G E2E system requires pervasive service management and orchestration (e.g., high resilience and availability), encompassing a comprehensive framework for data analysis, AI integration, and the coordination of RAN functions, transport network functions, 5G/6G CNFs. E.g., separation of control plane (CP) and user plane (UP), resilient mobility solutions, enhanced redundancy and recovery mechanisms.	Trustworthiness
6. Persistent security and privacy	The objective is to establish a comprehensive framework in the 6G E2E system that ensures security and privacy are integrated across all components with the goal of assuring a trustworthy environment. E.g., address current as well as future threats in a resilient manner and incorporate security fundamentals in its design, inherently support the preservation of privacy, allow different levels of anonymity for future services.	Trustworthiness
7. Internal interfaces are cloud optimized	This effort centers on the deployment of cloud-native virtual network functions, emphasizing the development of exposure interfaces that facilitate seamless communication between different layers of the 6G E2E system.	Sustainability, Trustworthiness
8. Separation of concerns of network functions	This refers to the optimized functionality in CN and RAN with bounded context and no duplication, avoiding complex interdependencies and cross-functional signaling- Self-sustained NFs with minimal dependency on other network functions.	Trustworthiness
9. Network simplification in comparison to previous generations	This initiative aims to avoid many standardized deployment options and protocol splits. It also involves the evolution of the 5GC to accommodate the requirements of 6G RAN. The focus is on simplifying protocols and minimizing User Equipment Network (UENW) signaling.	Sustainability, Inclusiveness
10. Minimize environmental footprint and enabling sustainable use cases	This principle aims for E2E orchestration, emphasizing energy-efficient and cost-conscious operations. It involves the implementation of a pervasive data and analysis framework alongside the modularization of network functions. The infrastructure layer in the 6G E2E system should optimize both energy consumption and costs for enhanced sustainability and operational efficiency of the use cases.	Sustainability

6. *Persistent security and privacy:* With the increasing number of services that handle privacy-sensitive data or controlling critical functions in industry or society, it is imperative to ensure that the systems will not be breached or compromised and that the use of data within the network is transparent and controlled. Thus, the security and privacy measures need to be pervasively incorporated throughout the system.
7. *Internal interfaces are cloud optimized:* As more and more IT systems migrates to cloud environments, it

is important to design 6G from the start to support deployment in cloud environments. A key factor for this is the interfaces between the network functions that should be designed to allow maximum potential service reuse and allow a service innovation with minimal integration effort.

8. *Separation of concerns of network functions:* To allow optimizations and automation should be as independent as possible, to avoid complex interdependencies and cross-functional signaling to provide particular services.
9. *Network simplification in comparison to previous generations:* Although each generation of mobile network provides improved, expanded, and additional services it's important to allow efficient deployment and operation of the networks, without unduly increasing the need for testing and verification of various deployment options.
10. *Minimize environmental footprint and enabling sustainable use cases:* As one of the major challenges facing our society today, the environmental impact of the 6G system must be minimized both in terms of greenhouse gas emissions, as well as, e.g., material use and other waste. For instance, the 6G system can be scaled up or down as needed, and to ensure that functions and entities can be turned off when not needed, both in the CN and the RAN. At the same time, 6G offers the potential to improve the impact of other sectors of industry and society through mobile digitalization, which should be considered when designing the 6G system.

B. IMPACT ON 6G E2E SYSTEM DESIGN

This section describes the relevance between the architecture design principles and their impact on the design of the 6G E2E system blueprint, which is presented in Section IV. The mapping of design principles and their impact on the 6G E2E system is summarized in Table 3. A blueprint describing the 6G E2E system should capture the main functional areas and indicate important interfaces both internally and externally. An important objective is to show the relation to well-established communication network architectures (e.g., RAN, CN and transport network) and indicate how to integrate beyond-communication functions. In addition, it is important to demonstrate how services and functionality will be exposed to applications and users.

IV. 6G E2E SYSTEM BLUEPRINT

As stated in the above sections, 6G will act as a platform providing a flexible set of services to the applications, adapted to the current needs and requirements. On the platform, the network will expose a diverse set of interfaces to applications, users, and verticals, which can be extended over time. As a technical realization of the 6G platform, the 6G E2E system is designed according to the architectural principles outlined in Section III-A. It should provide an efficient framework for integrating the new functionalities and novel technologies developed for satisfying the requirements from 6G. Moreover, with 6G being a platform serving applications, it is also important to demonstrate how services and functionality will be exposed to applications and users.

Consequently, the initial 6G E2E system blueprint, as developed by the Hexa-X-II project, is depicted in Figure 3 and consists of four main horizontal layers, i.e., Application layer, Network-centric application layer, Network functions layer, and Infrastructure layer, complemented by a set of Pervasive functionalities [24], [25]. Note that, as compared to the 5G system (5GS), the proposed 6G E2E system blueprint spans beyond the ambit of the 5GS. Specifically, the novel aspects of the 6G E2E system blueprint are as follows:

- The proposed blueprint introduces the infrastructure, network centric application, application layers, pervasive functionalities as well as the corresponding interfaces towards their interactions. In comparison, the 5GS focuses primarily on the network functions layer. These interfaces need to be carefully designed and defined to provide efficient linkage between the corresponding layers as shown in Figure 3.
- The proposed blueprint introduces the beyond communications functions as well as the 6G Core network functions blocks an extension to 5GC as compared to the 5GS. Moreover, considering the migration principles, the proposed architecture focuses on the 6G RAN network functions, only connecting to the 6G Core NFs without any non-standalone interworking, thus eliminating the possibilities of having multiple options as compared to the 5G paradigm.
- The proposed blueprint via the network-centric application layer and the 3rd party application layer introduces the full ecosystem applications that can interact with the underlying network. In comparison, the 5GS via the network exposure function (NEF) and network data analytics function (NWDAF) only exposes the possible APIs that could be used by applications.
- The proposed blueprint introduces the infrastructure layer that encompasses all of the E2E infrastructure and resources. It also introduces the cloud continuum principle, which will be essential for the 6G E2E system as discussed later in this article. On the other hand, the 5GS does not discuss all the aspects of the infrastructure as well as the possibility of a cloud continuum that extends towards the extreme edge.
- The proposed blueprint, introduces the AI framework which highlights the AI-centric approach to the 6G E2E system as compared to the 5GS. Furthermore, the management and orchestration framework moves beyond the traditional relevant functions in 5G networks towards a more intent-based approach. Hence, the proposed blueprint introduces the Intent based Management framework as one of the pillars of the 6G management and orchestration framework.

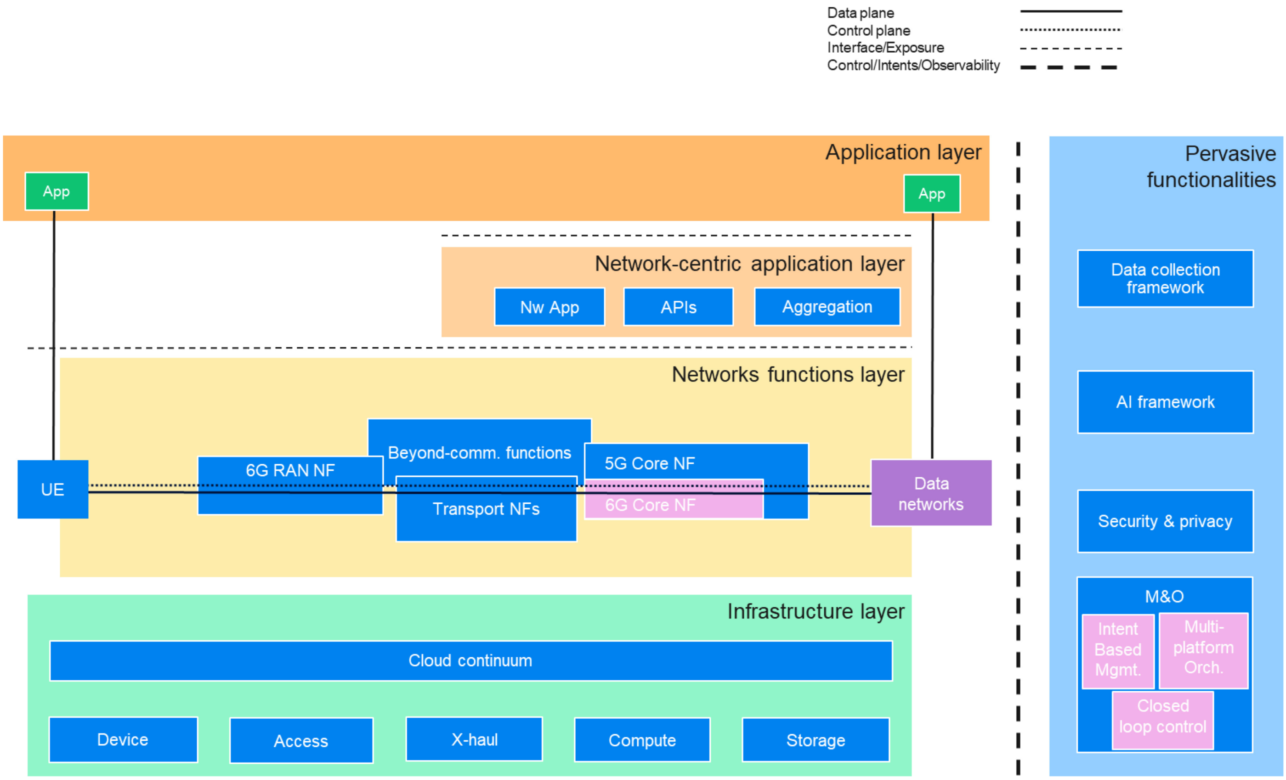

FIGURE 3. The proposed 6G E2E system blueprint [24], [25].

- Lastly, given the evolving nature of the 6G system and other technologies, the security and privacy threat vector space is also evolving. Consequently, a broader security and privacy framework for the 6G E2E system is required as against a more localized and domain specific approach on different layers of the 5GS.

Next, each of the components in the system blueprint are presented in further details.

A. APPLICATION LAYER

The application layer mainly represents the end-user or enterprise-centric applications that have certain service expectations from the network, such as bandwidth, latency, computing resources, analytics, and AI services. The 6G system is expected to support several new use-cases and applications (i.e., as shown in Figure 2). These needs at the application layer pose challenges on the QoS framework and provide opportunities for optimizations across different layers. Such cross-layer optimizations on both the network and UE side may dynamically adapt the QoS to various radio conditions and application requirements, improving as a result the end-user experience and keeping the 6G system complexity low. To support such optimizations and satisfy the QoS needs of an application, the concept of network slice is introduced in 5G systems [40] and extended towards 6G systems [41]. However, a network slice is essentially meant to support communication services [42] while new 6G applications appear to jointly require other services such as compute or sensing. Thus, a 'digital' slice concept extending the network slice concept appear to be necessary. To offer integrated communication and compute services or JCAS services, a digital slice instance should integrate not only networking but also other resources such as compute and sensing. For instance, immersive experiences such as extended reality (XR) where E2E application latency requires the consideration of both network latency (i.e., network metrics) and processing latency (i.e., compute metrics) giving the way to the convergence of network and compute [43], [44]. Collaborative robot applications, on the other hand, require the integration of JCAS capabilities [45].

B. NETWORK-CENTRIC APPLICATION LAYER

This layer consists of applications centered on network capabilities and under network operator control to provide enriched services to vertical applications. In the context of 6G systems, network-centric applications emerge to increase automation and distributed intelligence characteristics of the network services ([44], [46]). Where applicable, they take advantage of increasing in-network capabilities such as Data Management and AI techniques [44], [46], [47], or compute [48], etc, with further integration (e.g., integration of network and compute as per IETF CATS working group).

These applications, being more centered on network capabilities and under network control, have been presented as a separate layer from the application layer which is more end user or enterprise centric. For example, a network-centric application could leverage APIs provided by RAN vendors to optimize the operations of the said RAN node (e.g., Radio Resource Management), which could be done by providing certain parameter updates to a RAN NF (e.g., Central Unit Control Plane) on the node. Another range of applications covers applications oriented to the customer use case but developed or acquired by the network operator and under the network control. An example would be an adaptive transcoder leveraging congestion protocols to deliver uninterrupted high-quality media streaming. Additionally, the network-centric application layer provides APIs to expose the network-centric services to developers of applications at the Application layer. Moreover, aggregation of services, i.e., the action to compose services from a set of capabilities of different 6G service providers, e.g., over multiple networks, is also provisioned.

C. NETWORK FUNCTIONS LAYER

This layer consists of the logical network functions residing in the UE and subnetworks in which devices manage coordination and communication amongst themselves either independently or via network-based coordination, as well as the new beyond-communication functions which extend the traditional RAN, CN, and Transport network functions, with, e.g., novel RF-based sensing, and mapping functionality, advanced network-aware and mobility-aware computing services, and data analytics services. Stronger cooperation between the Data Network (e.g., edge computing) and the CN functions will help regarding the requirements in terms of E2E QoS of time-critical edge applications. Services and functionality in the Network function layer can be exposed through APIs directly to the Application layer, or through the Network-centric application layer.

As examples of the new services that 6G will offer are computing and sensing. Apart from utilizing computing resources to process the data and to enable the provisioning of its new services, the 6G network should expose them as a standalone service to applications, to support computation offloading of their computation-intensive tasks [49]. Research on architectural enablers to support computation offloading as a service across the computing continuum comprising multiple tiers, including edge and the cloud, is required.

As far as the RAN protocol layers are concerned, the 6G innovations should focus on reducing their implementation and operational complexity, enhancing security, decreasing latency, and minimizing the time to market. For example, enhancements to the RAN protocol security, could decrease the ciphering complexity, while also protecting L2 headers, which are unciphered and partially not integrity protected in 5G. Additionally, novel functionalities in the current RAN data recovery and reordering procedures would be required to decrease the added latency and jitter of Radio Link Control – Acknowledge Mode (RLC AM). The evolution of multi-connectivity, both in the context of harmonizing the carrier aggregation and dual connectivity features, as well as in the context of aggregating different access networks is expected to have a major impact in the 6G RAN.

Research on the traditional features is also needed. Mobility is one of the traditional radio features that makes cellular systems unique and that impacts the system KPIs. Ensuring seamless mobility is a critical aspect of 6G wireless networks to maintain continuous connectivity and enhance user QoE [50]. 6G RAN mobility solutions should aim to strike a balance between signalling overhead, complexity, and uninterrupted connectivity, supporting diverse scenarios such as high throughput, low latency, and high reliability. Key features like conditional handover (CHO) and Layer 1-Layer 2 triggered mobility from 5G and 5G-advanced should be enhanced, while leveraging technologies like AI/ML and Distributed Multiple Input – Multiple Output (D-MIMO) to optimize energy consumption, minimize service interruptions, and ensure QoS at the target cell. Additionally, the cellular measurement framework should be enhanced to meet the requirements of higher frequency bands and measurement demands in 6G. Furthermore, the role of the 6G RAN in providing beyond communications services, and the necessary updates to Layers-1 and 2 need to be investigated in detail.

Another dimension that needs to be investigated in 6G is the topology of the cellular system. 6G research should investigate how to integrate seamlessly trustworthy subnetworks, flexible topologies, and NTN to address various use cases and enhance digital inclusion and service coverage. New roles and functionalities of the devices/nodes should be defined and the coordination between devices and the overlay RAN BS in 6G networks should be investigated. For the NTN systems, the RAN will not only be impacted by determining which functionalities of the BS will be deployed on a satellite and which functionalities will remain on a ground BS, but also by determining the interworking between connectivity to terrestrial base stations and to non-terrestrial base stations.

D. INFRASTRUCTURE LAYER

It consists of the actual low-layer (i.e., physical layer) infrastructure such as the device hardware, the access and X-haul infrastructure (base stations, satellites for NTNs, packet routers and switches, optical transport network (OTN) switches, fibers), compute and storage facilities. Collectively, these can be managed in a cloud continuum from the central data network potentially all the way to the end-user devices. The transmission resources in the infrastructure layer allow the transmission of data from one end of the network to another. Furthermore, computational infrastructure across the computing continuum (IoT, extreme edge, edge cloud computing resources) is made available to support the deployment of virtual functions provided through the network-centric application layer and the network functions layer, as well as application components from the application layer.

6G radio access needs to be highly flexible for addressing the diverse needs of various use cases and deployment scenarios while simultaneously enhancing key value metrics. The 6G access infrastructure will go beyond 5G communication capabilities to include radio sensors for integrated sensing functionalities and incorporate technologies like Reconfigurable Intelligent Surfaces (RIS) [51]. Moreover, new devices categories will be deigned and optimized for specific applications, from low-data rate energy harvesting devices to high data rate devices used in AR/VR sets [52].

The access layer of the 6G E2E system will integrate a wide range of deployment types and radio architectures, each tailored to specific environmental characteristics, coverage requirements, mobility conditions, and connection densities. This includes not only conventional fixed cellular setups but also other scenarios like device-to-device (D2D) communications [53], cell-free/distributed MIMO [54], and the integration of NTN/ terrestrial networks (TN) [55]. Moreover, 6G access will cater to temporary deployments, where mobile infrastructures, such as flying base stations, are critical [56]. The 6G access infrastructure will be optimized for multiple coverage options, ranging from localized networks in personal devices or body area networks to wide area coverage. Furthermore, various frequency ranges will be exploited for different objectives, ranging from lower frequencies for coverage to higher frequencies for ultra-high data rates and enhanced radio sensing [57]. The inherent flexibility of the 6G infrastructure will provide significant opportunities for E2E optimization during operation, enabling a more adaptable and efficient network ecosystem.

E. PERVASIVE FUNCTIONALITIES

These include the functionalities and the frameworks that are needed to realize the full potential of the 6G platform, i.e., a collection of technologies for communication and beyond which also facilitate the four horizontal layers of the 6G E2E system blueprint either independently or jointly.

1) DATA COLLECTION FRAMEWORK

The data collection framework provides the necessary functionalities to support several different types of data and information to be collected from multiple domains and layers of the network and shared within the network for analysis. Novel approaches that support cloud-native observability are considered, where various types of signals are collected and processed, aiming to produce knowledge from the collected information [58], [59]. Such approaches are in accordance with the open telemetry specifications [60].

By the term signals, we refer to different types of monitoring data that may regard QoS metrics (e.g., link latency, packet loss, jitter), resource consumption metrics (e.g., average CPU/memory usage, incoming/outgoing traffic), metrics specific for a virtual function or microservice (e.g., service provision rate, processes packets per second), metrics related to distributed traces (e.g., software latencies for the execution of a software part or the interaction between microservices), and information coming from logging systems (e.g., health check of software components, availability, reliability). A set of monitoring probes and tools have to be made available for collecting these signals in the various parts of the infrastructure, considering the storage and processing points of the collected data. For instance, in the case of data coming from IoT infrastructure, processing and analysis may have to take place at the extreme edge part of the infrastructure. On the other hand, for the deployment and lifecycle management of virtual functions and applications, data have to be collected and made available to orchestration entities that may be centralized or distributed.

In all cases, data fusion techniques require access to semantically interlinked data based on the adoption of data representation schemes. Over such data, open and extensible analysis processes may be developed and applied for the extraction of insights that can be fed to operational or business support systems of network providers.

2) AI FRAMEWORK

The AI framework supports a systemic application of advanced AI/ML techniques at all stages of the system, i.e., domain-specialized, and cross-domain AIs which cover multiple functional and protocol layers, AI-embedded network functions and devices, and potentially across all functionality/protocol layers. Compared to 5G, AI will have a more prominent role in 6G, with a data-driven architecture that supports distributed intelligence and a distributed AI platform. The main drivers for AI in 6G are new opportunities for leveraging the 6G infrastructure flexibility, coping with network and service management complexity, and supporting new revenue streams via novel services with benefits both for society and industry. Therefore, the AI framework may run through all the layers in the system blueprint and play a key role in other pervasive functionalities such as security and privacy, and management and orchestration. For instance, related to infrastructure layer in the blueprint, AI will enable cost efficient radio transceiver design that adapts to changes in radio channel and to mitigate or compensate radio hardware impairments [61]. The novel AI-empowered schemes will cover aspects from waveform and modulation, radio channel estimation, and high throughput decoding, to E2E optimization of radio transceivers [13]. The aim is to outline a framework for the standardized AI in L1 for enabling AI/ML-specific features over the air and supporting AI-capable devices in harmony with legacy devices in the radio network.

3) SECURITY AND PRIVACY

Security and privacy considerations should be addressed in all the layers of the 6G E2E system and other pervasive functionalities. Contrasting markedly with 5G's emphasis on safeguarding against conventional threats such as eavesdropping, spoofing, and jamming, the 6G framework introduces a paradigm shift in security and privacy considerations. Moving beyond its predecessor's role as a conduit for data transmission, 6G emerges as a pervasive intelligent system inherently reliant on AI to deliver nuanced services. The attack surface of 6G will significantly evolve due to many factors such as the incorporation of novel 6G technologies, architectural evolutions, introductions of new use cases, and the advancement of adversaries [22]. In particular, due to the introduction of new services beyond communication, the 6G security and privacy challenges will significantly increase.

For instance, in a JCAS system the security threats should be clearly identified with respect to multiple assets, including the sensing information, the E2E system of sensing producers to consumers, the values provided to the operator from the sensing service, and the values provided by sensing applications [25]. The data gathered by JCAS about the users and passive subjects raises privacy concerns, especially in socially sensitive contexts. Therefore, it is crucial to proactively comprehend the privacy challenges associated with JCAS. Within the JCAS framework, privacy encompasses the collection, processing, ownership, and safeguarding of personal data derived from sensing measurements and outcomes [62].

The attack surface evolves alongside changes in network architecture, especially with cloud-native deployments, RAN disaggregation, open APIs, orchestrator frameworks at multiple levels, and resource federation among multiple stakeholders. Ensuring the security of 6G communications involves a focus on integrating Quantum Key Distribution and post-quantum cryptography to address long-term network security challenges, particularly those that may arise in a post-quantum era [63]. This evolution of 6G brings to the fore a spectrum of sophisticated risks, including intricate attacks on ICT infrastructure and data integrity challenges posed by malicious, albeit authorized, users - a scenario where users may either be inherently malevolent or compromised by external malefactors. Such a transformation necessitates a reevaluation of the E2E system design, steering away from the conventional KPI-centric approach towards a broader, value-oriented framework (which will be discussed in more depth in Section V-A). In this context, key values, particularly trustworthiness, assume a central role in appraising the system-level intent of each distinct use case. This refined approach is instrumental in orchestrating network operations, ushering in trust-centric methodologies like the reputation-based Trust-as-a-Service (TaaS) [64]. These innovative strategies signify a pivotal transition to a trust-focused network architecture, underscoring the paramount importance of integrity and reliability in the expansive 6G ecosystem.

The 6G E2E system design, underpinned by the principle of persistent security and privacy, emphasizes a comprehensive framework to ensure trustworthiness and multi-level security. This is especially critical given the innovations in the 6G system, such as the streamlined application layers, diverse network function topologies, and the integration of edge and end-user devices into a compute continuum. These advancements present potential risks, including data exposure through novel and simplified APIs, potential privacy breaches in new network scenarios, and increased vulnerability of user-critical data in less trustworthy edge devices. Therefore, the design of the 6G network must not only address these emerging threats but also proactively anticipate and mitigate potential risks through adaptive and trust-oriented security measures [65]. Critical components of multi-level security in 6G networks may encompass diverse security measures, featuring adaptive authentication, authorization, and selective data encryption techniques [66]. This involves leveraging sustainable AI/ML algorithms for zero-touch security implementation [67], implementing energy-aware security policies, deploying distributed security measures with dynamic adjustments (e.g., moving target defence) [68], adopting zero-trust security models with fine-grained access control [69], and establishing hierarchical security architectures with security levels across a network of networks, incorporating edge-level security processing [20]. The design and implementation of context aware security [70], post-quantum cryptographic algorithms [63], robust AI/ML model validation and testing protocols [71], data anonymization and encryption techniques such as zero-knowledge proof [72], mechanisms to isolate and secure third-party applications, assuring supply chain security [73], and developing remote attestation mechanisms are some key research areas that should be further investigated to tackle security and privacy challenges in 6G.

4) MANAGEMENT AND ORCHESTRATION

The management and orchestration framework should be designed to provide the appropriate levels of programmability, flexibility, scalability, and reliability to support the 6G use cases and applications and fulfil the associated KPIs and KVIs [74]. First, to overcome the limitations of classical management and orchestration for transport and cloud networks that are currently based on monolithic software, a novel cloud-native micro-services approach should be used [75]. The management and orchestration will leverage flexible function and resource allocation through heterogenous domains, as well as flexible topology realizations. Monitoring and telemetry interfaces as part of the aforementioned data collection framework will exploit real-time streaming to gather the state and the energy consumed by the network elements, enabling sustainable networking through energy-driven decision-making and will be the first enabler for the creation of digital twins (DTs), to feed AI-assisted autonomous networks.

Another crucial enabler for 6G networks is the programmability of the network to be able to configure and adapt to more than ever changing traffics and characteristics of 6G services [76]. With the new use cases of 6G and their more stringent performance requirements for certain types of traffic, it is also critical that transport and services are orchestrated jointly [77].

In contrast to 5G, dynamic traffic load pattern at the edge of the access will be more significant and 6G is expected to rely on a continuum of high number of heterogenous resources from extreme edge/devices (including end-user devices), edge nodes up to cloud resources, connected through multiple network domains whose boundaries will be blurred through horizontal federation or by the aggregation of elements across domains. This leads to much higher complexity from the management and orchestration perspective and thereby the classical centralized approach considered in 5G networks need to be revisited. A distributed but coordinated continuum management across multiple domains should be addressed, jointly for both network and compute resources [78]. We further discuss the multi-platform orchestration in Section VI-D.

In addition, to handle the ever-increasing complexity of heterogeneous multi-domains and multi-clouds, 6G requires zero-touch management [67]. It calls for the introduction of higher level of automation to transition to autonomy in network operations. With 6G being AI native, AI/ML will be applied in more comprehensive manner across 6G networks. AI/ML predictions will be extensively use for more proactive network management. The design and implementation of AI native control mechanisms are critical in the network management architecture to fulfil 6G KVIs with especial attention to energy efficiency optimization. Furthermore, the intent-based management approach will simplify the interface to operations leveraging the systemic application of advanced AI/ML techniques for closed loop control [79]. The intent-based system will have the capability to make the service requests from the users as easy and agile as possible and allowing the possibility to use a wide range of vocabulary (i.e., each user may speak differently) to deploy similar services, including sustainability specific targets as a key novelty. As 6G paradigm shift to trustworthiness as a key value, the design of the intent-based system should improve the security and compliance of digital environments. To do so, intent-based requirements can be defined to specify the desired behavior of the system and guide the system to automatically enforce service performance and security policies, and to ensure that the infrastructure is always achieving the expected tenant requirements and in compliance with the relevant regulations and industry standards. The co-existence of many different services and their specific service performance, security and trust requirements among multiple tenants can result in intent conflicts. These conflicts can arise when multiple tenants request conflicting actions or compete for resources, leading to performance issues or downtime. Therefore, a key aspect in a multi-tenant environment is the design and implementation of an intent-based conflict resolution solution. We further discuss the significance of closed-loop control automation and intent based network management in 6G in Section VI-D.

V. DESIGN PROCESS OF 6G END-TO-END SYSTEM

The design process of 6G E2E system may consider not only the value outcome from technology usage through KVIs and the performance requirements through KPIs for multitude of 6G use cases, but also the development of technical solutions adhering to the architecture design principles and the components from the system blueprint. In this section, we identify this as an iterative design process, which can be described in a two-fold manner as below.

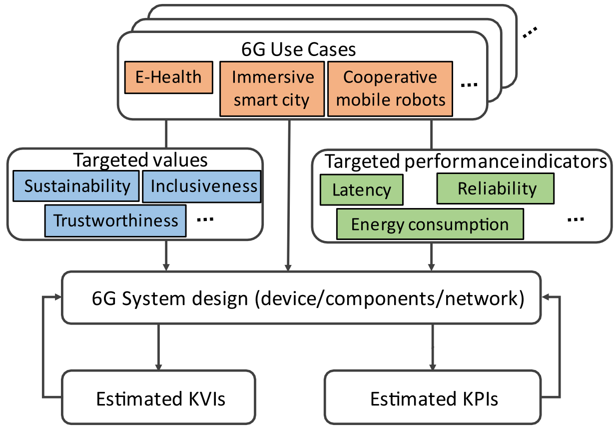

FIGURE 4. Top-down versus bottom-up approaches for iterative E2E system design process [24].

A. KPI AND KVI BASED DESIGN PROCESS

In Figure 4, the KPI and KVI based design process considers the requirements provided by 6G use cases with a preliminary set of targeted value and performance indicators. Note that a practical implementation of the design process is presented in Section VI.

Next, an initial 6G system design is performed considering the functionalities and integrating the components and enablers required for the use case requirements.. Then the evaluations of the 6G system design can be performed through the system-level proof-of-concepts (PoCs) or simulation-based approaches to estimate KPIs and KVIs where the results can be fed back for iteratively improving the 6G system design. Designing the systems based on KPIs and KVIs may involve trade-offs due to potential performance decline from adhering to specific KVIs, necessitating their careful consideration in the iterative design process. Specifically, the evaluation will involve firstly whether the proposed components and enablers conform to the agreed upon KPIs and KVIs corresponding to the use case. The different components and enablers in the E2E system will contribute individually to several KPIs such as latency, cost, energy consumption and even reliability. The overall design process will study the allocation of E2E additive KPIs as provided amongst critical components integrated within the E2E design. The standalone design process for each component could be compared to the measured KVIs provided by the evaluation and validation processes.

Next, distinct strategies or design choices will be applied depending on the pursued values. For example, the sustainability value consideration will have an energy consumption

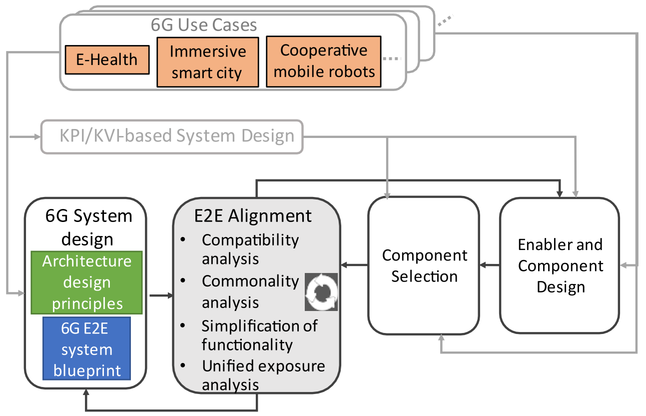

FIGURE 5. KPI/KVI-based iterative system design process [24].

reduction objective, among others, which requires considering the system-level integration of multiple technologies such as energy-efficient radio, adaptive transport protocols, AI/ML for dynamic resource and service optimization, and zero energy devices. Then, it is necessary to assess the overall consistency of operations across the different components of the 6G system and to verify the capabilities to fulfil the targeted KPIs and KVIs. The trustworthiness value consideration will require the assessment of possible additional risks introduced, what translates in assuring the AI based components are explainable, interpretable, and fair to avoid any bias, as well as in evaluating how privacy and security are preserved. This requires considering the consistency in holding the properties of trustworthiness from end to end at each sub-layer of the system layer, to be analyzed through the security assessment mechanisms. This is also applicable to the enablers of a trustworthy relationship between the stakeholders involved in the E2E service delivery chain.

B. TOP-DOWN VERSUS BOTTOM-UP ALIGNMENT PROCESS

In this sub-section we discuss the top-down versus bottom-up alignment process as demonstrated in Figure 5. The top part of the figure represents simplified depiction of use case dependency and the previous KPI/KVI based iterative system design process.

First, the top-down approach involves an iterative design process wherein the system blueprint for the sustainable, inclusive, and trustworthy 6G platform will be elaborated based on the 6G use-cases requirements and the system architecture design principles. As new use cases and associated KPIs/KVIs will be studied during the development of 6G, the system requirements will need to be frequently revisited, and the considered set of technology innovations will accordingly be refined or augmented. Conversely, consideration of the technical achievability will give feedback for fine-tuning the use cases and for the consolidation of KPIs and KVIs.

Second, the bottom-up approach designs and provides the different components of the system in separate tasks. The component selection process considers pros and cons of each potential enabler and component developed or considered for achieving the 6G E2E architecture objectives. A checklist of what can be considered in technical components/enablers for the alignment with the E2E performance and operation targets can then be used as feedback towards enabler design as well as E2E system design. The E2E alignment process especially carries out several analyses that are further detailed below. The analysis results will serve to continually update the 6G system blueprint as well as the component design, as enablers and components become more mature.

The E2E alignment process necessitates to conduct a thorough analysis in terms of compatibility, commonality, simplification, and unified exposure of the components.

- **Compatibility analysis**: When integrating different enabler components together in an E2E system, it is crucial to verify the capability of these enablers to work with each other. For example, whether a proposed protocol/interface provides compatibility to work with other parts of the 6G system. Additionally, the security and privacy implications of the use of these enablers and their interplay must be assessed, incorporating the required controls for addressing them. To illustrate, consider two enablers: one called 'Distributed compute as a (beyond communication) service' (A) and the other named 'Convergence of communication and computing' (B). For seamless integration, enabler A needs to offer enabler B an exposure interface that B can easily understand. Enabler B can then utilize this interface to choose and allocate the appropriate computing resources, taking into account the optimal solution for both the converged network and computing aspects.
- **Commonality analysis**: As distinctive design activities apply the same design principles; it might happen that similar components will be elaborated in separate ways for distinct enablers. The analysis work will look for and detect those component commonalities and help in the selection of one common component. This allows for some mutualization amongst various global 6G design activities. Similarly, different replicas of the same information spread across the system in a distributed manner could possibly be centralized and reused.
- **Simplification of functionalities**: The detection of commonalities could be considered as the first step to simplification. Optimization of the interaction between functions or modules could also be performed to reduce the latency budget (e.g., E2E User Plane latency or Control Plane procedure latency) and meet the requirements. Within this context, one may consider the possibility of merging some adjacent components, turning their mutual interfaces into internal interfaces. Impact evaluation should be provided in this case.
- **Unified exposure analysis:** This will check for uniformization across the various exposure of new interfaces between the network and the vertical service

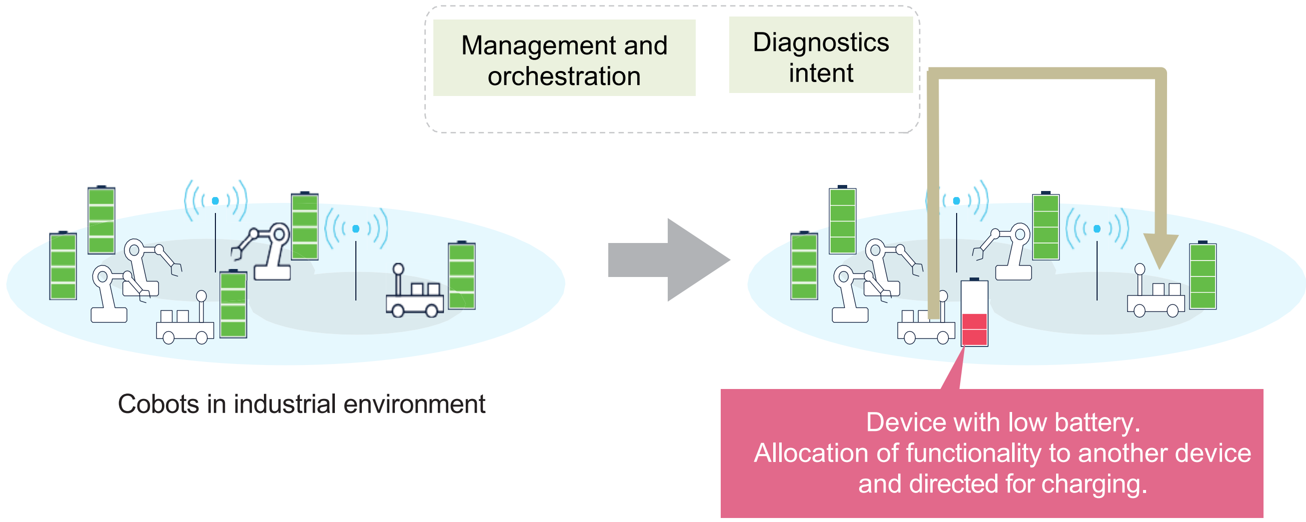

FIGURE 6. A triggering instance of the cobot use case where the workload of a cobot with battery depletion is replaced with another cobot [24].

providers The security exposure functions, provided by the 6G platform for developing new secure and robustness services using API framework, should be also analyzed. The exposed APIs can provide analytics, such as network energy measurement, latency, throughput, localization, and sensing information.

VI. DEMONSTRATION OF 6G E2E SYSTEM DESIGN LIFECYCLE

Given the detailed system design process developed by Hexa-X-II project, presented in Section V, we now demonstrate the practical functioning of this process by considering the technological innovations being considered for an exemplary cobot use case (i.e., as a PoC). Note that the technological innovations vary greatly depending on the scenario and use case, where they allow 6G E2E system to meet the technical requirements. Additionally, they may span through single or multiple layers of the proposed system blueprint based on their functionalities and capabilities as well as the requirements coming from the use cases. In the considered use case, technological innovations are considered with respect to management and orchestration enabler.

A. USE CASE

The use case considered (i.e., shown in Figure 6) comprises of several collaborative mobile robots, also known as cobots cooperating in the context of an industrial environment and conducting various tasks related to warehouse inventory management as a part of manufacturing process, such as product identification, quality inspection, and registration. In this scenario, a group of cobots, with certain hardware (e.g., battery, mobility, sensing related), compute, and network capabilities is assumed.

Resilience and efficiency in such industrial scenarios require robust and trustworthy management and orchestration of the involved resources, energy efficiency, as well as seamless reconfiguration in case of malfunctions, errors, or resource scarcity. Such errors may comprise hardware impairments (e.g., cobot arm impairment), unexpected battery depletion, network anomalies like increased packet error rates for a specific device. Such events are handled as triggers for the management and orchestration framework for instant re-configuration of resources (i.e., as shown in Figure 6). Besides reactive, proactive actions may also be applied, leveraging predictive AI/ML-based capabilities. The expected behavior is for the energy-depleted or malfunctioning devices to be seamlessly removed from the industrial task process (towards being repaired), while the tasks assigned to the former must be reallocated to the remaining devices.

The need for 6G in industrial scenarios, as the one studied here, can be attributed to several factors. In the specific use case, uncompressed ultra-high video quality transmission for the highest data quality possible is required for teleoperation and virtual reality (VR) applications. In addition, to ensure a safe navigation of robots through teleoperation in a warehouse environment while guaranteeing, efficiency-wise, a minimum robot speed (corresponding to respective number of teleoperation commands per second, between the application server and the device), extremely low latency and high reliability are of critical importance. Moreover, leveraging the network – compute convergence, AI workloads will be able to be dynamically placed across the continuum in a native manner, enhancing this way real-time data analytics, predictive maintenance, and intelligent decision-making processes, ensuring sustainable network operations, efficiency, and privacy.

The proposed use case consists of and relies on a set of advanced functionality components across all four layers of the proposed 6G E2E system blueprint, i.e., Application, Network-centric application, Network functions and Infrastructure layers. As part of the Application layer, the warehouse inventory management enterprise application components related to the cobots' operations, planning, navigation and inventory audit are assumed. Those application components have certain service expectations from the network not only related to throughput, latency, computing resources, reliability, but also beyond communication services, namely sensing, analytics, AI services. To this end, network-centric application layer can provide certain enriched services to the enterprise application components via the related exposure APIs, related to RAN analytics, e.g., for dynamic, adaptive, AR-powered tele-operation service, or sensing data for optimizing path planning services. The 6G NF capabilities respectively, as part of the Network Functions layer, spanning from RAN NFs up to the 6G Core domain, and including communications- and beyond communications (i.e., compute, AI, sensing) related functionality supporting the E2E services. For example, for the collaborative robots' use case, RLC AM enhancements may be needed for reducing the added latency and jitter; sensing-related functionality NFs (i.e., network- or cobots/UE-centric) should also be supported and orchestrated in a resource efficient manner, along with the compute and AI resources available. Last but not least, the infrastructure layer is providing the actual communication (e.g., warehouse NPN infrastructure), and computing resources (across the IoT/cobots, edge and cloud computing continuum).

B. KVIS AND KPIS

To address the above objectives, the use case is expected to be validated towards addressing target KVIs such as minimizing detrimental effects of sustainability and trustworthiness-oriented orchestration in 6G. The operations of the cobots with an energy efficient perspective will maximize the lifetime of the operations. The improved human-machine interaction in the given use case with the intelligent cooperation among cobots via management and orchestration of the 6G continuum, and resource-usage efficiency will impact the overall operations in the manufacturing process by maximizing the lifetime of the operations in a resource limited environment. Handover of the operations in a general failure will assure the resilience of the system and thereby enhance the trustworthiness. For this reason, novel energy-efficiency optimizing, as well trust assessment components will be integrated in the E2E system architecture, while the interdomain (AI, application, edge, cloud, network) resource management capabilities of the system will be demonstrated.

Next, KPIs offer a means to gauge and monitor specific metrics affecting network performance, beyond communications service performance, as well as user perceived service quality. In this context, the identification and continuous tracking of appropriate KPIs become crucial for fine-tuning network performance, upholding QoS standards, and ensuring a flawless user experience. Considering the cobot use case, and with respect to the smart network management aspects of 6G E2E system, following are some examples of KPIs that can be utilized [24], [25].

- Network reliability as a measure of time percentage for which the network is available and functioning correctly.
- E2E communication latency.
- Provisioning time in the cobot use case pertains to the time it takes to configure, set up and prepare for the given industry automation task.
- Beyond communication aspects, such as sensing and localisation-related data collection, processing time, and accuracy.
- Time to terminate the operations of one cobot from the termination request up to the release of its assigned resources.
- Time to recover the operations in the industry zone at an energy-depletion of one cobot, providing a measure of the reactiveness of the network in minimizing service down time.
- Time to deploy E2E intent-based service request and make it available with respect to the needs of cobot assisted industry manufacturing use case.
- The power consumption of the cobot for a pre-defined set of configured roles/actions, per unit of time.
- The power consumption measured for all involved system components, for the E2E service execution, per unit of time.
- A set of indicators for measuring the trust of all the entities/nodes, allocated in the E2E service, including end-devices (e.g., cobots), as well edge/cloud compute nodes.
- Intent conflict resolution latency which refers to the time to achieve the complete resolution since an intent-based conflict is detected, up until it is solved.

C. TOP-DOWN APPROACH

We now present the top-down approach of the 6G E2E system design process with respect to the cobot use case. For this process, the input data may encompass the existing elements and their attributes, which include their control and programmability capabilities, energy consumption, deployment considerations, and service requirements. Within this context, AI mechanisms for control and programmability of 6G focusing on energy consumption aspects can be demonstrated and resources can be assigned in a manner that optimizes energy consumption while considering security and performance. Moreover, the solutions may use programmability and consider zero-touch to automate the reconfiguration and energy-aware self-optimization at runtime as well as the usage of a network digital twin for action verification or intelligent agent bootstrapping. Since AI takes a critical role, the AI models providing these functionalities should also be hardened-by-design to protect against possible security and privacy attacks targeting the AI model itself.

Additionally, there can be multitude approaches to relate intent-based scenarios with the given cobot use case. For instance, responsible domain-specific management and orchestration components can re-configure the resources towards various intents, such as the maximization of the lifetime of the cobot swarm operation (thus, the allocation of

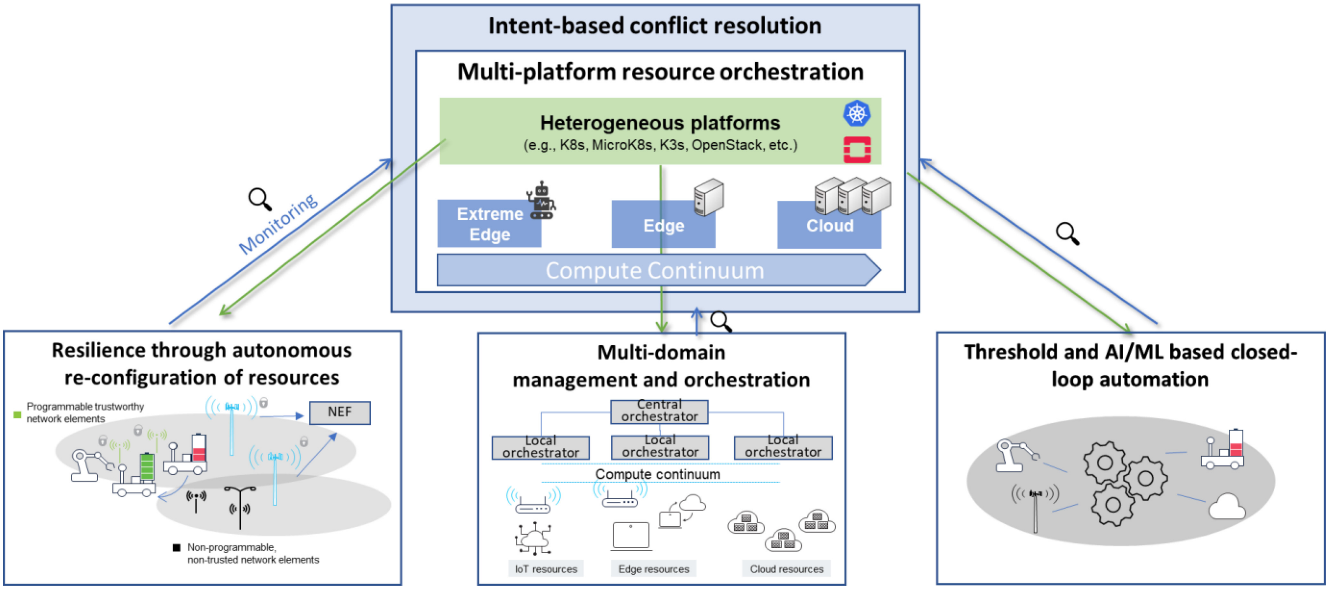

FIGURE 7. **Overview 6G enabler distribution for the cobot use case aiming for sustainable and trustworthy-oriented orchestration in 6G [25].**

resources towards minimizing the energy consumption rate of the overall system). Additional application features may comprise the capability for the user to make requests related to the warehouse areas or sectors to be inspected by the cobots and respective allocation of ground or aerial nodes (i.e., automated guided vehicles (AGVs) or unmanned aerial vehicles (UAVs)), the sensing and exposure to the user of environment-specific information inside the warehouse (e.g., location of products/items, identified obstacles).

Adhering to the steps presented in the design process and to cater the above discussed functionalities, we consider the 6G enablers for management and orchestration and diagnostic elements. More specifically, we utilize three enablers for the cobot use case, which on a broader level are encompassed under multi-platform orchestration, automation and intent-based management. Notably, these are mapped to the pervasive functionalities described in the proposed 6G E2E system blueprint (i.e., in Section IV-D). Moreover, few of the design principles discussed Section II-C can be easily related with the demonstration of the given use case (e.g., resilience and availability, full automation, and optimization, and minimize environmental footprint and enabling sustainable use cases). As depicted in Figure 7, a multi-domain environment is illustrated to represent the flow of the cobot use case. Accordingly, the multi-platform and the multi-domain orchestrators (top and bottom-middle boxes in the figure) will be utilized for autonomous repair operations (bottom left-hand side box in the figure). Intent-based closed loop automation will also be adopted to facilitate the network and service operation during the service runtime while handling the versatility of the different aspects of the network (e.g., traffic, applications, devices), with the goal of optimizing the usage of the infrastructure resources (bottom right-hand side box in the figure). Through this top-down approach, we have determined the enablers that would not only aim to satisfy the use case requirements, but they would also adhere to the E2E system blueprint and design principles.

D. BOTTOM-UP APPROACH

As stated in the design process in Section V, in the bottom-up approach, firstly the enablers and components are identified considering key aspects for achieving the 6G E2E architecture objectives. To exemplify the bottom-up approach, from the extensive list of 6G technological enablers discussed in Hexa-X-II, here we identify three categories of enablers which are the most prominent in mobile collaborative robot use case to achieve smart network management aspects (i.e., as summarized in Figure 7). These enabler categories are grouped under multi-platform resource orchestrator, closed-loop control and automation, and intent-based management. As highlighted in the bottom-up approach, the continuous development results of these enablers will be fed to the necessary refinement of the 6G E2E system. Moreover, we would like to clarify that only a selected subset of technological enablers relevant to network automation are discussed below.

1) ENABLERS FOR MULTI-PLATFORM RESOURCE ORCHESTRATION

One main aspect that must be considered towards the deployment and runtime management of the cobots regards the management of resources made available across the computing continuum, from IoT to the edge to the cloud part of the infrastructure. Suitable representation and abstraction of the managed resources (e.g., IoT devices, IoT gateways, edge computing servers, cloud computing servers) must be provided to enable the application of orchestration actions over them [80]. Based on the abstraction of such resources, multiple management and orchestration solutions emerge that consider aspects related to the type of the deployment (e.g., network service, application with strict QoS requirements), the type of infrastructure (e.g., multi-cloud, multi-cluster, leased resources, IoT devices) and various deployment constraints (e.g., locality due to privacy, security, delay-intolerant application parts). For instance, in the cobot use case, a distributed application that supports the operation of the cobots is provided that can be deployed and orchestrated over resources in multiple clusters across the computing continuum.

To orchestrate such an application, there is a need for the deployment of multi-cluster management tools to support resources management actions (e.g., scaling, compute offloading, live migration). There is also a need for injection of autonomy and distributed intelligence characteristics to facilitate collaboration among multiple orchestration entities that may act at local (e.g., cluster) or global level. The exploitation of multi-agent systems and ML techniques is considered promising towards the development of autonomic management functionalities (e.g., autoscaling functionalities driven by Reinforcement Learning (RL) techniques [81]) and the support of distributed intelligence characteristics (e.g., based on multi-agent systems management and Federated Learning (FL) approaches [82]). One of the main distinguishing characteristics of the developed mechanisms compared to previous solutions targeted to 5G systems regards the transition towards synergetic orchestration mechanisms. In this case, multiple agents need to collaborate by having joint global goals, while in parallel being able to support decision making in their local cluster. In this case, each agent is responsible for management of resources within a specific cluster, while the agents may collaborate to guarantee service level agreements (SLAs) for the E2E network. In a 6G ecosystem, various types of synergies may be specified and applied. In case of deployment of distributed applications or services across resources in the continuum, synergies among multiple orchestration agents are applied. Synergies may be also developed among peer network or infrastructure providers, as well as among network providers and OTT players (e.g., application providers).

The application deployment requirements (e.g., locality constraints in case of the cobots, minimum resources usage, dedicated bandwidth in a specific link, low latency service) have to be properly declared and communicated to network operators or network management platforms to deliver the required network infrastructure and instantiated network services to address the application needs. Intent-driven approaches can be proven very helpful towards this direction, however by considering the need for the development of formal intent-description models (or languages) that can be adopted by the industry. Intent translation mechanisms have also to be developed, considering the existence of multiple agents for enforcing orchestration policies to the various parts of the infrastructure. As already mentioned, synergetic orchestration mechanisms are to be exploited for managing deployments over resources that may span across the computing continuum.

Energy efficiency is a critical aspect where AI can play a significant role in improving energy efficiency of the 6G network. In this context, we need a high energy efficiency of AI (data, training, inference) which makes impact on reducing energy of the network and participate in reducing the carbon footprint in cities and in industry. For instance, AI/ML will play important roles for orchestration of 6G E2E network slicing. Context-aware policies are certainly major options to adapt service delivery to changing user needs, environmental conditions, and business objectives. By addressing the problem of optimal placement of dynamic virtual networks through a self-adaptive learning-based strategy, orchestration AI/ML-based satisfies functional KPIs and participates in reducing energy consumption. Using algorithms such as Deep Reinforcement Learning (DRL) combined with other strategies [83], [84], it participates to reduce learning cost time, computing resources, and sensitive to changes in the network. The autoscaling orchestrator allows adjusting the number of virtual network functions (i.e., CNFs) in a telecom cloud platform corresponding to the devices demand (e.g., cobots in this case). Autoscaling participates in reducing energy consumption and infrastructure cost when scaling down. However, the adjusting process produces the delay resulting on instance creating to make services available with the enough resource. The predictive mechanisms with workload forecasting based AI/ML can enable the improvement in performance of the autoscaling orchestration system. The more robust the models or the algorithms are, the more precise the estimation of the number of instances by the autoscaler [85]. The latter instantiates just needed resources during the traffic load lifetime to optimize the energy consumption and the infrastructure cost. Microservices must be thus able to scale, increasing or decreasing dynamically the number of resources consumed and consequently the quantity of serviceable demand.

2) ENABLERS FOR CLOSED-LOOP CONTROL AND AUTOMATION

The concept of closed loop (CL) control is essential to provide higher levels of automation in the orchestration of the E2E cobots' services. This reduces the need for manual intervention for the operators, which would become too risky or even unfeasible in highly scalable and complex environments.

The closed loop control functions provide autonomous cycles of observation, analysis, decision and actuation stages on specific services or resources, taking actions to guarantee the fulfillment of target objectives [86]. In the cobots scenario, this approach provides fundamental support for the operators, contributing effectively to the safety of the entire operations. First, CL control avoids the burden of continuously monitoring the multitude of service components and the complex telemetry of heterogeneous resources, which span from multi-technology network elements and computing nodes up to IoT devices. Moreover, it provides an efficient support in taking complex and risky decisions which impact the efficiency and the continuity of the service. The actuation of these decisions can be fully automated or require a final manual confirmation under the supervision of the operator.

The CL as an enabler for the network and service automation is not entirely a 6G novelty. Several 5G and beyond research projects have investigated and exploited the concept to automatize the control of specific elements of the mobile networks and/or implement specific use cases. In [87] and its follow up [88], control loops have been utilized to demonstrate some automation use cases for network healing, optimization and protection while, in [89], [90], they are used for the automatic management of networks slices in terms of scaling and migration, respectively.

Nevertheless, conversely to the 6G approach, where the stages of the CL can be implemented by specialized and orchestrable functions, 5G counterparts are mostly pre-provisioned with limited configuration capabilities. This is often implemented by exploiting existing elements of the mobile management systems, i.e., monitoring facilities and orchestrators/controllers, supported by an analytics and a decision process very specific for the targeted automation and not always based on AI/ML techniques. This result in a limited control of the CL at runtime, with almost no possibility to retrieve crucial information for the management of the loop itself, e.g., CL goal(s), target resources, current status. Multiple closed loops are possible but hard to coordinate at runtime. Introduction of novel specific entities for managing CL lifecycle and coordination, enables 6G systems CLs to go beyond the limitations characterizing the previous network generation.

The usage of advanced techniques of AI/ML may further enhance the efficiency of the CL control. ML-based analysis and decision stages can go beyond the classical reactive automation by adopting proactive and predictive approaches to anticipate re-configuration actions or re-optimize the distribution of tasks across large fleets of cobots. Cooperative decisions can be taken exploiting distributed AI techniques and applying multi-criteria objectives, e.g., to jointly reduce the recharging period of inactive cobots and schedule additional application processes on computing resources embedded in cobots engaged in low-complex tasks to obtain an optimal load balancing. RL techniques and mechanisms for continuous validation of ML models can guarantee a smooth adaptation of the CL logic in dynamic scenarios where cobots are engaged in tasks changing and reconfigurable in time. Trustworthy and explainable AI techniques can inform the operators about the reasons of some optimization suggestions, enabling a more effective troubleshooting and providing contextualized motivations to drive final decisions and actuation commands.

Multiple instances of concurrent CLs can run in parallel, each of them specialized to manage a particular type of resource, handle a given objective, or target subsets of cobots. These CLs become an integrated part of the network system and need to be modelled and orchestrated following the same principles, guaranteeing full interoperability with the rest of the management functions. The closed loops' logic is thus decomposed in a set of virtual network functions that are deployed, activated, and configured dynamically through a CL governance service. The interaction, cooperation and coordination among multiple CLs allow consistent decisions on the whole set of resources, at the network, computing, and device level, delivering the E2E service offered by the cobots. For example, a CL guaranteeing the continuity of the transport network connectivity between edge nodes shall be coordinated with the service-level CL in charge of selecting the computing resource placement and migrating the service components. Such coordination can be established through delegation and escalation procedures of interdependent CLs, with peer-to-peer or hierarchical interactions.

In scalable scenarios with large fleets of cobots, highly dynamic tasks and widely distributed applications across edge and cloud domains, concurrent CLs may lead to conflicting decisions that can be hard to detect and mitigate. In this case, digital twinning techniques to preliminarily validate the mix of decisions can help to identify and predict the impact of the various actions on a digital copy of the target environment before their actual enforcement.

As mentioned, CLs can be provided with high level of automation by the means of including ML algorithms where they can assist to tackle more complex management schemas, as the ones needed to manage resources as the extreme edge of the compute continuum. In 6G we are expecting end user devices offering much more communication and computing capabilities, thus services can be also deployed seizing the computing resources at the devices as the extreme edge, this is much closer to users, and consequently improving performance in terms of latency and speed. However, the compute resources at the extreme edge present important challenges from the management and orchestration perspective given its high dynamic and volatile nature, thus AI/ML can be of great potential to assist in helping to predict such a potential changing behavior.

As stated above, AI/ML is bringing very important benefits in terms of automation to network management and orchestration and thus reducing Operational Expenses (OPEX); however, it is bringing new challenges that need to be considered. ML models need a previous training process that is not negligible in terms of invested time and increase of computational resources, and therefore bringing a resulting negative impact in terms of latency if this is not well managed. Finally, considering the critical environmental sustainability target in 6G, AI/ML can be used to incorporate prediction capabilities when implementing energy-aware network management to be more energy efficient and even achieving further energy savings by means of taking proactive decisions. But at the same time AI/ML would be bringing its own energy consumption

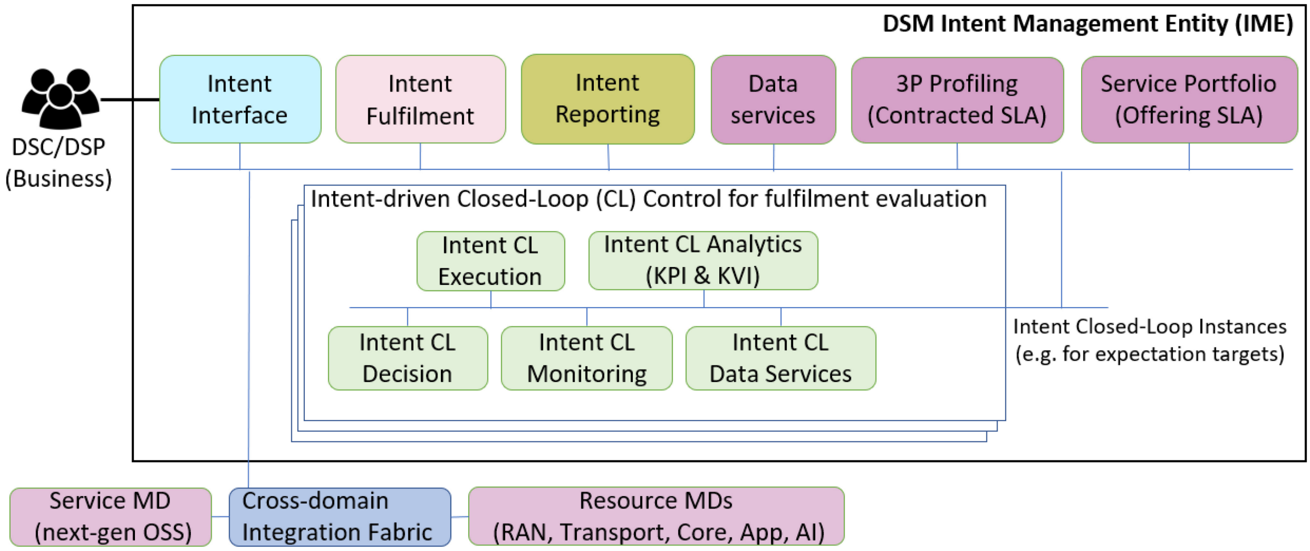

FIGURE 8. Intent-driven placement design mapping to functional blocks [25].

increase, especially on the ML training phase, when the significant computing process takes place [91]. Therefore, the optimal balance between reached performance and energy consumption should be found. Furthermore, it is not only about the energy-efficiency or energy consumption reduction, but more importantly about reducing the actual carbon footprint and CO2 emissions so mechanisms to move to green energy sources should be prioritized. Estimation of the expected energy saving from concrete ML algorithms will need to be compared with the actual expected increase of energy consumption due to the associated model training, to take decision whether implementing them or not, and in case of positive decision, evaluate how, when, and where.

3) ENABLERS FOR INTENT-BASED MANAGEMENT

The main objective of intent-based management (IBM) is to remove the need to know the details about the infrastructure resources and which specifications are required to manage (i.e., create, configure and terminate) services within a network. By using intents, the user only uses an abstracted request to define what is the desired service, and it is the system itself which must identify how to achieve what is requested, from the translation of "human" request towards the necessary set of "system" requests in an autonomous way. This automatic translation can be done using AI/ML techniques such as natural language processing or large language models [92], [93]. In terms of initial research and standardization work, there are different works focused on IBMs. However, the existing methods are mostly vendor specific and script-based solution which requires highly human involvement. On the other hand, IBM is the future for network automation, and it opens the door for a standardized and multi-vendor available automation tool.

One of the first documents in terms of standardization is presented in the RFC 9315 [94], where the basic concepts and definitions about IBM are presented. Recently ETSI Zero-touch Network and Service management (ZSM) group has presented their first group report [95] about how intent driven autonomous network should be and work. As defined by the technical reports [96] and [94], the Intent Management Entity (IME) may play two different roles: the intent owner and the intent handler. The first is the intent source/requester and must take care of its intent lifecycle, being the only one that can manipulate the intent itself. Moreover, the 3GPP presented their specification [97] of IBM on mobile networks, defining the object data models and the management actions during an intent life-cycle.

6G systems are characterized by a high-level of automation that requires the usage of control closed-loops at all levels, including intent management. Also, 6G services are being consumed by increasingly different types of applications, each with its specialized requirements and domain-specific context addresses a wider range of use cases by employing more granular intent specifications. Each intent instance is defined by a set of parameters. As the number of intent instances grows, robust and scalable solutions become essential to effectively store intent information and track intent configuration changes. Within the Hexa-X-II context, it is proposed that intents management should be offered by a Digital Service Provider (DSP), able to deliver E2E intent-based services by applying an intra-DSP management or by interacting with other DPS domains with cross-DSP components of multiple stakeholders (i.e., federation) [25]. Therefore, scalable and flexible IBM with higher autonomy level and the capability of providing interactions between network and diverse 3rd party application providers are the key for IBM in 6G vision. With this vision, we propose the following functional architecture illustrated in Figure 8. In there, the IBM solution for a DSP called as digital service management (DSM) intent management entity (IME) is presented through its eight functional blocks:

1) Intent Interface: This component is the core element of the architecture as it takes care of the receiving the tenant (i.e., DSC/DSP) requests, generate the intent objects associated and manage the lifecycle of the intents by using the internal functions offered by other functional modules and the resources in the Management Domains (MD) below. To begin with, this component is the gateway for the user to interact with the whole DSM IME and trigger those actions available for the user. Its main capabilities are: a) the interpretation of the incoming source to translate (if necessary) the incoming data into an IBM data object, b) to show to the user which are the capabilities offered by the DSM IME solution, c) to offer CRUD Create/Read/Updated/Delete) operations, d) to deal with the intent activation and deactivation when required, and finally, e) to frequently interact with the Intent Reporting functional module to obtain the associated reports of each managed intent.
2) Intent Fulfilment Internals: This block has those capabilities that a tenant should never be able to have access or to care about but, that are key to those capabilities visible by the user. Among them, there is the translation function that allows to translate the identified intent expectations into the right action requests that will be implemented through the use of CLs, moreover the feasibility check function to validate if the received intent may be applied. Furthermore, the functions regarding the governance and coordination of CLs associated to each intent, and, finally, the intent conflict detection and resolution functions. Such conflict detection and resolution can be leveraged with different techniques such as natural language processing for explicit conflict withing an intent or multi-objective optimization when there considering multiple conflicting intents [98].
3) Intent Reporting: This functional module focuses on the multiple types of intent-related information (i.e., Intent Feasibility Check Information, Intent Fulfilment Information, Intent Conflict Information) to generate the associated report for each intent and inform about their specific status when requested. It is worth noting that each section in a report, will be filled in when necessary. For example, if no conflicts are generated, that specific section should remain empty.
4) Intent-driven CL Control for fulfilment evaluation: This functional block offers the capabilities to manage the life cycle of the Intent CL instances and ensure they are fulfilled at any time. To do so, the capabilities are a) Intent CL Execution, b) Intent CL Analytics (KPI & KVI), c) Intent CL Decision, d) Intent CL Monitoring, and e) Intent CL Data.
5) Data Services: This functional block is in charge of storing all information related to the generated intent data objects and their reports, in addition of other possible information such as SLAs and policies.
6) 3rd Party (3P) Profiling: This functional block allows providing a full characterization of every tenant (i.e., a 3rd party) through a 3P profile, captures tenant-specific information on security (supported credentials and access control solutions), trustworthiness (relevant in federation scenarios), contracted services and SLAs, and end-users.
7) Service Portfolio: It focuses on offering the available 6G services information to the tenants, so based on the available services and their information, tenants may request with more knowledge better intent-requests. Among the service information available, there are aspects such as their status (i.e., defined, designed, built, tested, released), their owner, variabilities over the same service (i.e., SLA and offerings), costs or dependencies with other services.

Based on the presented functional architecture and considering the use-case example where the cobot which has a critical energy level can generate an intent pointing to its energy issue that must be solved until a particular time deadline, the intent life-cycle is presented in Figure 9. This is a high-level requirement that we expect to see in 6G systems [96]. With "Intent translation and provisioning" this intent can be translated to a service intent and sent to necessary network domains, as shown in step 1 of Figure 9. This translated intent will be (optionally) decomposed in multiple intents or instructions to fulfill the intent expectations, as shown in step 2 of Figure 9. This decomposition could mean having different domains. Each domain (i.e., RAN) can have different responsibilities and actions to fulfill the intent's expectations. Once the intent is decomposed on the different network domains, "Closed Loop Coordination" is run within an Intent Management Coordination framework. In this framework, at each domain different intents are managed by trying to avoid any conflict between each other, as shown in step 3 of Figure 9. Here, actions are taken autonomously in a closed-loop fashion. Ideally, the Intent-based management autonomously fulfils the expectations of all intents. However, since resources are shared within a domain, conflicts may arise due to not fulfilling the intent's expectations. Thus, it is critical to detect any conflict before it happens, as the intent's expectations can be time-critical or can cause significant damages, translated as costs. Therefore, the impact of each proposed action to fix the issues must be predicted and possible conflict should be managed in advance, which "Intent Conflict Administration", as shown in step 4 of Figure 9. Optionally, the Intent-based Management can send reports about the intent's expectation fulfillment and conflicts between intents, as shown in step 5 of Figure 9.

It is important to highlight the fact that many of these functions are being actively investigated in key standardization organizations. For example, TM Forum and 3GPP identify intent interfaces, intent model and reporting. ETSI ZSM works on closed-loop control operations and integration fabric, etc. In this sense, it is a critical task from an implementation perspective to get all these functions together

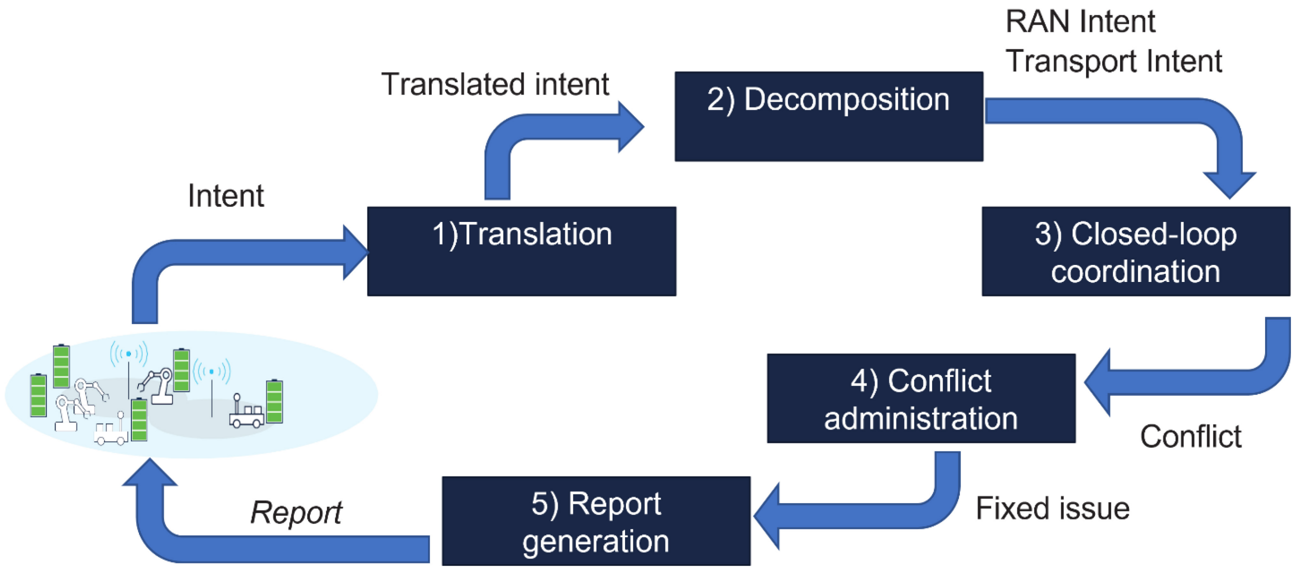

FIGURE 9. Intent-based Management flow example.

to work coherently. We also note that these functional blocks are mapped to the blue-print architecture given in Figure 3 although it is not explicitly shown in the figure. We envision to see certain level of autonomous operation in all of the network domains. Therefore, intent-based operations and consequently the functional blocks in Figure 9 will be an integral part of the autonomous management. For example, an intent-handling function can have a hierarchical structure where a more holistic intent-handler can place in M&O domain (i.e., OSS) and a lower-level intent-handler can operate in RAN, Core or Transport domain of the network. More specifically, different intent-handlers with using the functional blocks in Figure 9 can be distributed in network and infrastructure layers in the blue-print architecture. In this regard, intent-based operations with the proposed functions will occupy a significantly crucial role in supporting autonomous management and operation of 6G vision.

Further to those three categories of enablers summarized above related to smart network management and orchestration, more enablers are to be introduced in the use case implementation in the next steps. One direction concerns novel architectural enablers, which will enable the formulation of flexible network topologies in a dynamic and trustworthy manner. Another set of enablers will leverage architectural enablers and further introduce beyond communication aspects, i.e., enablers, which will offer sensing, localisation, compute, AI and other types of resource exposure, from the network towards the application layer, via respective novel interfaces. Finally, 6G radio aspects and 6G device components will be included in the evolution of the cobot use case development to showcase the technological advances.

VII. VIRTUAL MODELING

As was introduced in the previous section, demonstrations done by PoCs are highly important in the iterative 6G system design roadmap. In this section, it will be introduced how the virtual modeling approach can support the system design and performance evaluations. Indeed, the usage of simulation or emulation-based modeling and DTs are envisaged to increase remarkably in the 6G solutions early-phase design and performance evaluation [99], [100]. Virtual models are becoming more accurate and valuable due to enhanced calculation power of computers' central and graphical processing units, as well as sophisticated software development capabilities. Virtual modeling will directly contribute to sustainability of the design process, by enabling that system performance can be accurately simulated, instead of physical measurements to be performed in the field, or in the lab environment. The trend is that novel solutions will be virtually modelled, as much as possible, before manufacturing the physical prototypes, leading to decreased cost and improved resource efficiency. DTs are also envisaged to be used for run-time control of the 6G real systems for performance optimization of the desired KVI and/or KPI, by using bi-directional interfaces between the DT and physical system [101].

Due to abovementioned reasons, virtual modeling and digital twinning is here suggested to be used for the 6G connectivity solutions performance evaluation, already in the early design/research phase, to verify the fulfilment of KVIs and KPIs, and provide feedback in the iterative system design process. The purpose is to support 6G system design by focusing on the technical communication enablers, which are not feasible to be studied by using the PoC approach, during the research phase. Specifically, the goal is to study selected technical enablers proposed for 6G evolution [102], by mainly focusing on the RAN solutions, and their control & optimization. RAN is an important part of the architecture blueprint, enabling the planned 6G services by providing connectivity with the required QoS.

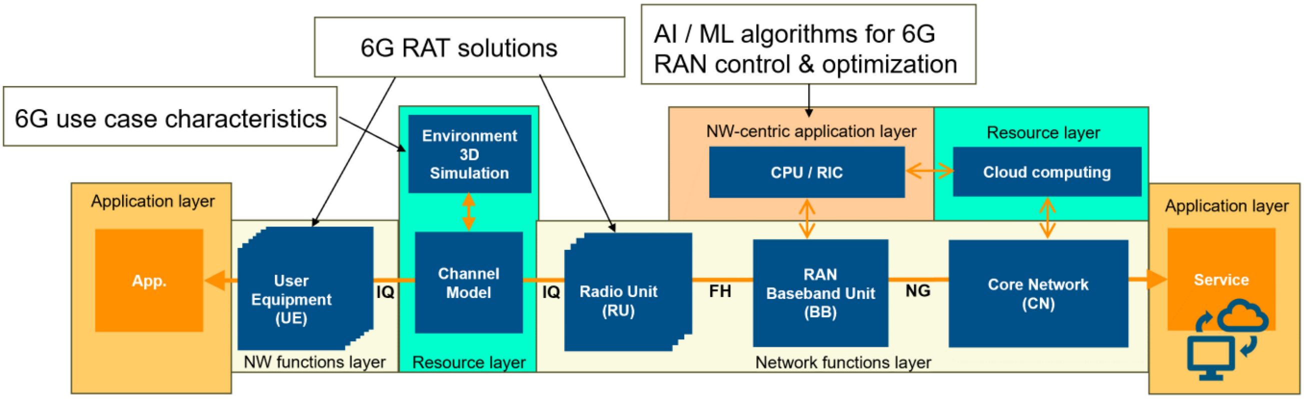

FIGURE 10. High-level architecture of the E2E simulation framework [25].

The high-level architecture of the E2E simulation platform, and its mapping to the proposed 6G system blueprint, is shown in Figure 10. As illustrated in Figure 10, the E2E simulation framework includes partial functionalities from each layer of the 6G E2E system blueprint. Application layer includes the service application, which creates traffic to be communicated between the core network and UE. Network-centric application layer includes the RAN (intelligent) control application, which can be assumed to be running, e.g., in a CPU at the edge cloud. The RAN control targets to optimize connectivity system performance, by taking advantage of the available information, such as the communication environment characteristics, user requirements, resource constraints, user location and channel conditions, which can be used as an input to AI-based control algorithms. Even the AI-based RAN control has been proposed already for 5G networks, it will most likely be much more advanced during 6G era. Network functions layer includes the CN, RAN BB, RU and UE. Note that depending on the proposed 6G solution, such as D-MIMO, there may be multiple RUs under single RAN BB unit. Resource layer includes additional computing resources, which can be used, e.g., for computing tasks needed for AI/ML - based control applications training data preparation, or for accurate modelling of the environment and corresponding channel models. In this work, the E2E simulation platform will be gradually developed towards 6G system as the new technological solutions and interface definitions appear.

Typically, the novel technical solutions will be at first evaluated individually at the link-level. The purpose of introduced virtual framework is to enable evaluation of novel solutions as a part of the E2E system, as well as to get more insights, during the iterative design process, about the requirements and potential challenges of the novel solutions' integration to the 6G system. Furthermore, many technical enablers proposed for the 6G system, e.g., D-MIMO, RIS and JCAS, also include AI-based control for performance optimization [102], [103]. The performance and reliability effect of the AI algorithms is very difficult to be evaluated resource- and cost-efficiently, without virtually modeling the E2E system. Due to abovementioned reasons, we highlight the potential advantages of virtual modeling and digital twinning for the future connectivity solutions design process, performance evaluation, as well as for the real-time performance optimization once the networks are being deployed.

VIII. CONCLUSION AND FUTURE WORK

In this paper, a structured and systematic approach towards the design of the 6G end-to-end (E2E) system has been presented. The proposed approach has been generated through extensive consultations, research and development spanning the complete value chain of stakeholders encompassed within the European 6G flagship project Hexa-X-II. Given the diversity of challenges that ensue the development of a complex system such as the 6G E2E system, in this paper the main aim has been to consider those challenges and develop the E2E system blueprint that adheres to both KPIs and KVIs. To this end, the various novel layers of the 6G E2E system blueprint have been described. Additionally, the corresponding technological innovations within each of the layers have also been highlighted. These technological innovations aim to achieve the given ten design principles and satisfy the use case requirements from the 6G system. Next, a novel design process is adopted to tackle the challenges of integrating a ever-growing set of technologies and services that the 6G platform should offered to meet the needs of society in 2030. This process consists of two aspects, i.e., KPI-KVI based and the top-down and bottom-up approach.

Lastly, in this paper, the design process is applied to a cobot use case and the corresponding enabler selection and system design process has been explained. Additionally, the virtual modelling and the corresponding simulation framework, which assists in the verification of the said system design, has also been detailed. Consequently, through this article, the first iteration of the approach to design the 6G E2E system has been concretized, which is aimed to assist the wider international community in their ambitions to develop the 6G system further. As next steps, the consortium will revise and hence, refine the 6G E2E system blueprint further as the concepts and approaches mature within the consortium and in the wider scientific community.

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