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Envisioning 6G Outlook and Technical Enablers*

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SUMMARY 6G research has been extensively conducted by individual organizations as well as pre-competitive joint research initiatives. One of the joint initiatives is the Hexa-X European 6G flagship project. This paper shares the up-to-date deliverables through which Hexa-X is envisioning the 6G era. The Hexa-X deliverables presented in this paper encompass the overall 6G vision, use cases and technical enablers. The latest deliverables on tenets of 6G architectural design and central pillars of technical enablers are presented. In conclusion, the authors encourage joint research and PoC collaboration with Japanese industry, academia and research initiatives for the potential technical enablers presented in this paper, aimed at global harmonization towards 6G standards.

key words: *6G, use cases, architecture, technical enablers*

1. Introduction

Approximately every ten years, the opportunity presents itself to define the next generation of mobile networks. While the roll-out of 5G systems has successfully evolved, with currently more than 200 networks being operational worldwide, the journey of 5G evolution will continue for another eight years with innovations coming as evolutionary steps under the umbrella of 5G Advanced. This will comprise solutions to enhance coverage, user experience, expand beyond connectivity and operational excellence.

At the same time, 6G research is in full swing together with strong momentum not only by individual organizations, but also from pre-competitive joint research initiatives in several geographical regions. In North America, Alliance for Telecommunications Industry Solutions (ATIS) has launched Next G Alliance led by private sectors, which is an initiative to develop the national roadmap for 6G and key and strategic areas towards 6G [1]. In China, IMT-2030 Promotion Group has been established to gather China's research activities for 6G [2]. Likewise, the similar initiative has been established in the other regions, such as 6G Global in Korea [3], Telecommunications Standards Development Society, India (TSDSI) in India [4] and Beyond 5G Promotion Consortium in Japan [5]. In Europe, several 6G initiatives have been launched, such as Smart Networks and Services (SNS) Joint Undertaking [6] and 6G-Access, Network of Networks, Automation and Simplification (6G-ANNA) [7]. Amongst the European 6G initiatives, Hexa-X has been the flagship European 6G research project established as part of the EU's Horizon 2020 ICT-52 program since January 2021 until the middle of 2023. The project is driven by a consortium of members representing key players from the industry and academia, with the goal to define the framework for 6G research and guide long term technology direction for wireless networks evolution in Europe. One of the key driving principles is to contribute towards harmonization of the global Vision for 6G and define technology foundations for end-to-end 6G networks in cooperation with stakeholders worldwide, which makes the Hexa-X project unique and differentiated from the other initiatives. The next European level 6G Flagship, Hexa-X-II, funded by the SNS Joint Undertaking, is ramping up already in the first half of 2023. In addition, continuing the work of Hexa-X, Hexa-X-II is also aiming to create the blueprint system design of 6G.

The Hexa-X vision is for networks to transcend the conventional function of beyond being bit-pipes into being the means to connect human, physical, and digital worlds. Technologies that enable such networks have to be built upon the pillars of sustainability, trustworthiness, and digital inclusion, keeping in mind the key challenges of the current and future societies. The project has identified six key research challenges — connecting intelligence, network of networks, sustainability, global service coverage, extreme experience and trustworthiness. The approach has been to guide the technology work on the basis of future use cases, and to transform the fundamental network design paradigm from mainly a performance oriented one that expands to also being value oriented, where the technical Key Performance Indicators (KPIs) are complemented with key value indicators (KVIs) to drive the network design.

To this end, several key use case families have been identified, which are key drivers to revolutionize mobile networks for 6G. Key technology enablers are being developed to realize these use cases which include sub-THz transceiver technologies, accurate stand-alone positioning and radio-based imaging, improved radio performance, AI/ML (Artificial Intelligence/Machine Learning) inspired radio access technologies, future network architectures, service manage-

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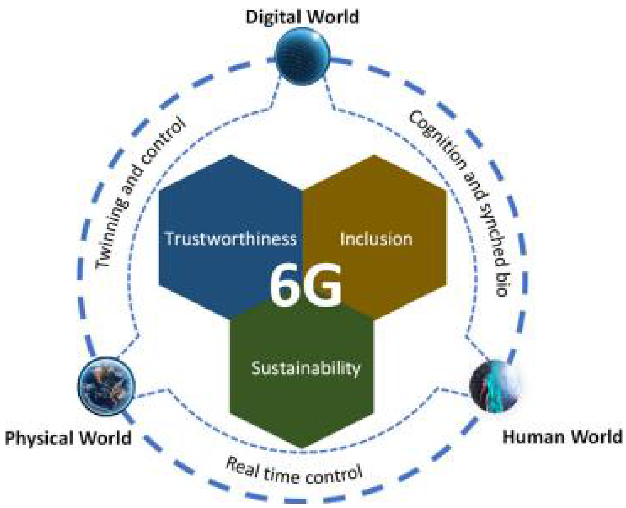

Fig. 1 Hexa-X 6G vision of connected worlds and key values [1].

ment and orchestration and special purpose solutions.

This paper shares the up-to-date progress delivered by Hexa-X, complemented with the tenets of 6G architectural design and technical enablers. Section 2 summarizes the outcome delivered by Hexa-X and future plans to be delivered. Section 3 explores the up-to-date 6G use case families. Sections 4 and 5 describe architectural themes of transformation and technical enablers for the target 6G use cases.

2. Outcome Delivered by Hexa-X

As the first milestone, Hexa-X formed the 6G vision to tightly couple and enhance the interactions between three worlds: a human world of our senses, bodies, intelligence and human values; a digital world of information, communication and computing; and a physical world of objects and organisms, as presented in Fig. 1 [8].

To characterize the 6G vision from the perspective of an end user and network usage, Hexa-X identified the following four objectives.

Objective 1: Foundation for an end-to-end system architecture
Objective 2: Radio performance towards 6G
Objective 3: Connecting intelligence towards 6G
Objective 4: Network evolution and expansion towards 6G

Several tasks are conducted for each objective to deliver the outcome of the relevant technical components. Table 1 gathers the Hexa-X deliverables published as of now and the summary of each deliverable. Hexa-X has been planning to produce further deliverables to finalize the research of key technical enablers as shown in Table 2.

3. 6G Use Cases

After the initial study presented in [8], the Hexa-X project made further progress in envisioning concrete 6G use cases. The Hexa-X project clustered the envisioned use cases into the use case families as described in [19], [21]. Figure 2 presents the up-to-date view of Hexa-X use cases and use cases families.

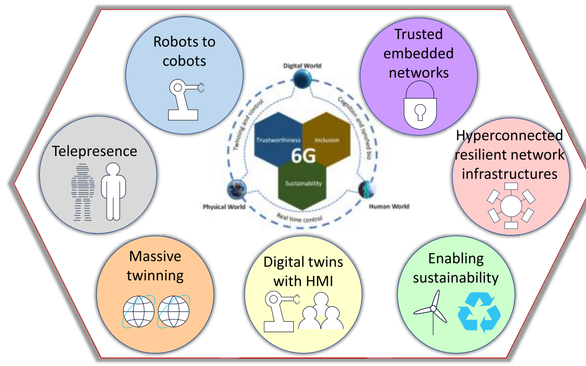

Fig. 2 6G use case families.

A. Enabling Sustainability

This use case family gathers various use cases relying on 6G as a tool to enable sustainability in other activity sectors. The following use cases are clustered into this family.

- E-health for all
- Institutional coverage
- Autonomous supply chains
- Sustainable food production
- Network trade-offs for minimized environmental impact
- Network functionality for crisis resilience

B. Massive Twinning

Massive twinning, i.e., the application of the more fundamental Digital Twin concept in a wide set of use cases, will gain importance. The following use cases are clustered into this family.

- Digital twins for manufacturing
- Immersive smart cities
- Internet of Tags

C. Telepresence

This use case family consists in being present and interacting anytime anywhere, using all senses if so desired. The following types of telepresence are envisaged.

- Fully merged cyber-physical worlds
- Mixed reality co-design
- Immersive sport event
- Merged reality game/work

D. From Robots to Cobots

The 6G system provides the technical fabric to go beyond

Table 1 Hexa-X public deliverables.

Deliverable title	Summary
6G vision, use cases and key societal values [9]	6G Hexa-X vision including aspects of novel use cases, services and key value indicators and performance
Expanded 6G vision, use cases and societal values - including aspects of sustainability, security and spectrum [10]	Extension of [9] to address impact of growth, sustainability, security and spectrum evolution aspects
Towards Tbps Communications in 6G: Use cases and Gap Analysis [11]	An initial insight into the current state of the technology for wireless communication in the frequency range of 100 to 300 GHz as well as other physical layer enabling technologies for future wireless communication systems
Gaps, features and enablers for B5G/6G service management and orchestration [12]	Analysis of the state of art for service orchestration and potential technical enablers for 6G service orchestration
Gap analysis and technical work plan for special-purpose functionality [13]	Initial study on technical enablers for extreme experiences in Internet-of-Things and Industry 4.0 environments
AI-driven communication & computation co-design: Gap analysis and blueprint [14]	Motivations for the utilization of Artificial Intelligence (AI) and, in particular, Machine Learning (ML) mechanisms in 6G systems and identify the major challenges that arise.
Initial radio models and analysis towards ultra-high data rate	Present first simulation models and analyses of the 6G radio
links in 6G [15]	and physical signal layer which will be used as a basis simulation framework for further studies
Localisation and sensing use cases and gap analysis [16]	Gap analysis between the current performance of 5G 3GPP localisation and radar and lidar sensing, and the target KPIs deduced from the Hexa-X use case families
Initial 6G architectural components and enablers [17]	Architectural components for 6G that support a new flexible network design, full AI integration and network programmability while, at the same time, streamline and redesign the architecture for a network of networks
Intermediate dissemination and communication report [18]	Summary of the dissemination and communication activities that have been carried out by Hexa-X partners during the first year of the project
Targets and requirements for 6G - initial E2E architecture [19]	6G Hexa-X novel use cases, services, and KVIs as well as KPIs
Design of service management and orchestration functionalities [20]	Design of service management and orchestration (M&O) functionalities for 6G, addressing the M&O architectural design of the novel orchestration and management mechanisms
Special-purpose functionalities: intermediate solutions [21]	Updated technical enablers for extreme experiences in Internet-of-Things and Industry 4.0 environments from [13]
AI-driven communication & computation co-design: initial solutions [22]	Solutions for distributed AI applications and communication & compute resource allocation to enable efficient AI platform
Initial models and measurements for localisation and sensing [23]	Initial findings towards models, methods, signals, measurements, and the protocols for localisation and mapping, as well as providing the vision of how accurate location and sensing information can enable and enrich applications
Analysis of 6G architectural enablers applicability and initial technological solutions [24]	Architectural components for 6G that support full Artificial Intelligence (AI) integration (a.k.a. AI native system) and network programmability, a new flexible network design, while, at the same time streamline and redesign the architecture for a network of networks.

pure command-and-control of individual robots. Instead, it empowers robots to become "cobots" in that they form symbiotic relations among each other to fulfil complex tasks efficiently or better cater to the needs and demands of humans in day-to-day interactions. The following use cases are envisaged.

Table 2 Upcoming Hexa-X deliverables.

Deliverable title	Delivery date
Radio models and enabling techniques towards ultra-high data rate links and capacity in 6G	April 2023
AI-driven communication & computation co-design solutions	May 2023
Final 6G architectural enablers and technological solutions	May 2023
Final evaluation of service management and orchestration mechanisms	May 2023
Special-purpose functionalities: final solutions	June 2023
Hexa-X architecture for B5G/6G networks – final release	July 2023
Enabling radio technologies and roadmap towards 6G	July 2023
Final models and measurements for localisation and sensing	July 2023
Final dissemination and communication report	July 2023

- Consumer robots
- AI partners
- Interacting and cooperative mobile robots
- Flexible manufacturing
- Situation-aware device reconfiguration

E. Trusted Embedded Networks

"Mobile" communications are up to today often "cellular" communications. Many use cases, however, require local or private communication capabilities for very sensitive information that are tightly integrated in wide-area networks. Here, network topologies beyond cellular topologies and security concepts beyond classical security architectures are required. The following types of embedded networks are envisaged.

- Human-centric communications
- Infrastructure-less network extensions and embedded networks
- Local coverage for temporary usage
- Small coverage, low power micro-network in networks for production & manufacturing

F. Hyperconnected Resilient Network Infrastructures

Similar to the trusted embedded networks, there exists use cases involving sub-networks or networks of networks, which require high level resilience. The following use cases are envisaged.

- Sensor infrastructure web
- AI-assisted Vehicle-to-Everything (V2X)
- Interconnected IoT micro-networks
- Enhanced public protection

G. Digital Twins with Human-Machine Interface

The concept of digital twin with Human-Machine Interface (HMI) and its massive deployment in the industrial 6G environment will play a key role to achieve the convergence of human, digital, and physical worlds. Figure 3 illustrates the overall ecosystem of 6G human-centric digital twins with the direction of information flow. The instantaneous observable states of the physical entities are continuously measured and uploaded to the computing nodes, which are usually located at the network edge for low latency, so that the digital twins stay as up to date as possible. Examples of such low-level status information are including but not limited to channel state information, computing resource availability, and user trajectory. Timely updating and archiving such data, industrial digital twins are capable of not only monitoring the low-level status of massive machines and humans in real-time or almost real-time, but also estimating high-level context information that is typically unobservable, such as the physical/mental health condition of humans, reliability of industrial equipment, or the possibility of malicious cyber-attacks. Leveraging such knowledge, we will be able to develop a 6G digital twin-based industrial ecosystem, in which the three worlds of data, machines, and humans converge into one. With ubiquitous, fast, and reliable connectivity for everything and everyone, the interconnection of physical entities and digital twins will significantly expand the ways in which humans and things recognize and interact, enabling several revolutionary emerging use cases:

Ubiquitous and Collaborative Telepresence: The 6G network will enable bidirectional data exchange between physical entities and their digital twins in a timely and reliable manner, allowing for virtual interaction with the former over the latter. Furthermore, with the ubiquitous coverage and high accuracy in time synchronization to be provided by 6G, the same digital twin can simultaneously interact with multiple individuals (or their digital twins) in arbitrarily different locations without triggering conflicts or collisions between the operations. Thus, a remote collaboration that works as smooth as on-site can be realized by means of telepresence, which will dramatically reduce the efforts and costs associated with spatial distance and access barriers.

Understanding the World: Staying connected and synchronized with everything involved in the physical environment, a digital twin-empowered industrial system can collect a massive amount of data. Thanks to the latest achievements in the field of AI and ML, the hidden coherence and causation between different events can be extracted from the data, which will certainly enhance our comprehension to the

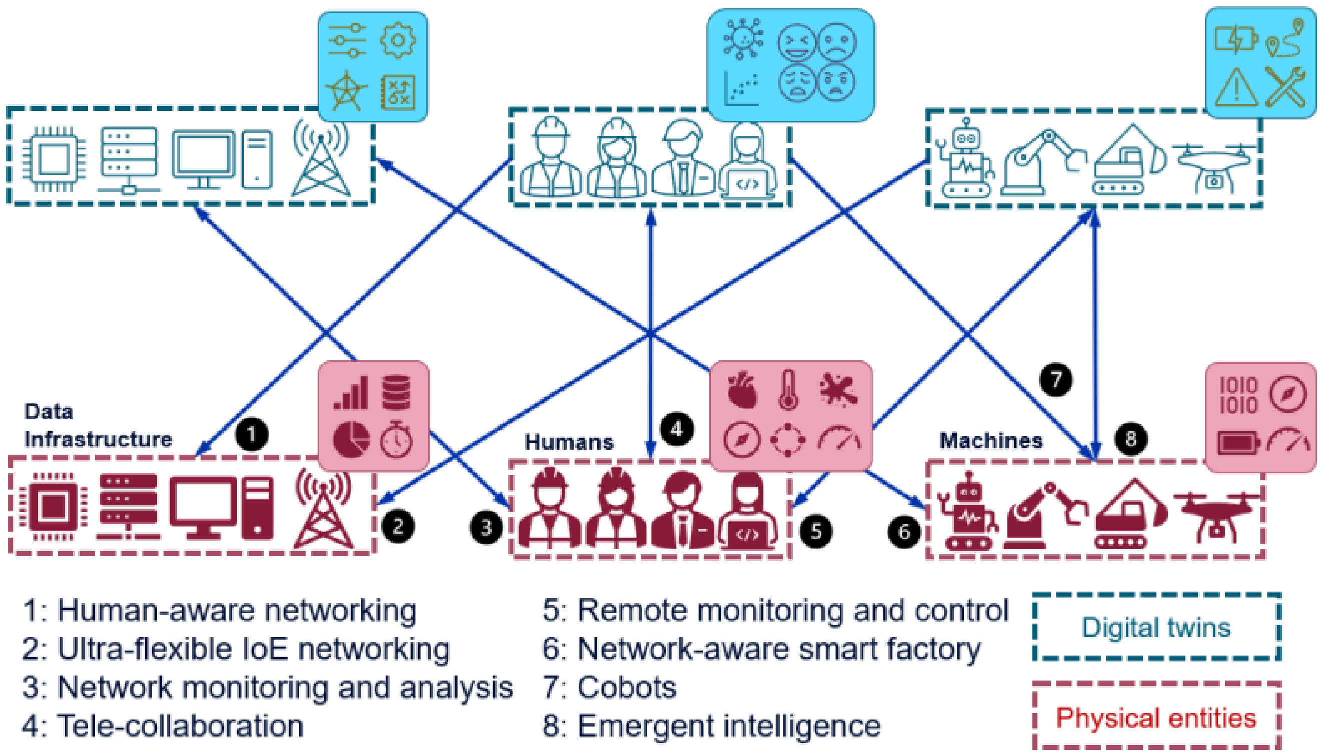

Fig. 3 Ecosystem of 6G human-centric industrial digital twins [7].

industrial equipment as well as the physical environment, and therewith help us to appropriately design, configure, operate, diagnose, and maintain them. On top of such comprehension, complex and collaborative interactions among different entities will arise from the meaningful and selective data exchange between their digital twins.

Understanding the Humans: While industrial equipment and the physical world mostly behave in a deterministic manner that can be precisely predicted upon an accurate model, human behaviour cannot be completely predicted. Therefore, human coexistence in industrial scenarios and human participation in industrial processes introduce significant uncertainty into the system, inevitably resulting in risks of service degradation and failure. Nevertheless, with massive data collected and analysed, the digital twins of human participators can create a statistical model of human behaviour that assists the industrial system in assessing and mitigating such risks. Furthermore, using multi-dimensional status information obtained via advanced human-machine interfaces, human digital twin can recognize higher-order human status that are difficult or impossible to observe directly (e.g., emotion or fatigue). Numerous additional benefits can be therewith obtained: dangerous situations can be avoided, assistance can be given whenever and wherever needed, and the "cost of interaction" in terms of complexity of interaction can also be reduced.

Sustainable Industry: On the one hand, with massive twinning, the status of all components and participants in industrial processes can be precisely monitored, and jointly analysed. This helps people to thoroughly understand the unobservable patterns hidden beneath the complex processes, e.g., the carbon trace and the energy consumption throughout the process chain. Therewith, the energy efficiency and sustainability of the industry can be improved. On the other hand, green communication and energy efficient computing solutions must be invoked to ensure the industrial deployment of 6G massive twinning itself being sustainable.

4. Architectural Transformation

For enabling the target use cases explained in the previous section, architectural transformation and associated decompositions have been studied extensively [17], [25]. This section describes the tenets of an architecture for 6G.

4.1 Architecture Design Goals

The 6G architecture needs to support a set of new use cases as described in Sect. 3, while still supporting existing use cases in an optimal manner. To address these requirements, the architecture is expected to evolve in 6 key areas as shown in Fig. 4.

Flexibility: The 6G architecture is expected to be more flexible to work for large-scale wide area network deployments as well as for extremely local on-premise and personal area networks. Also, a wide variety of latency targets and changing network loads, e.g. to support XR (Extended Reality)

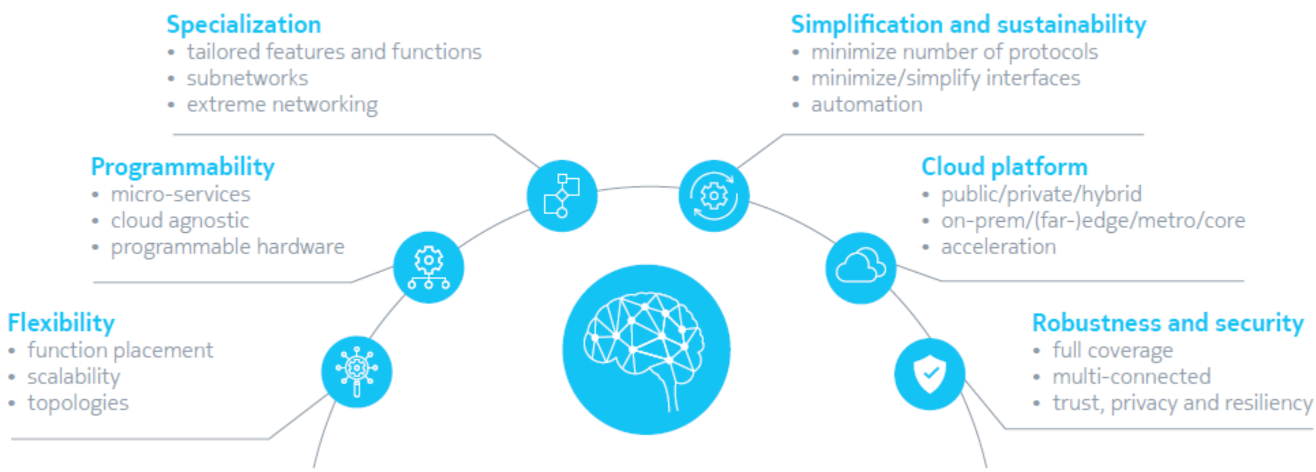

Fig. 4 6G architecture design goals.

services, would imply a need for dynamic scaling and reconfigurability in placement of network functions.

Specialization: There is a wide spectrum of deployments that are expected to be supported in the 6G era ranging from a lightweight sensor network, to extreme networking use cases for immersive communications. Each deployment may require a specific set of functions and not others, and hence architecture should be amenable to allow specific personalities (combination of functions) to be instantiated depending on the needs of the use cases and deployments.

Availability and Robustness: Given the target to achieve ubiquitous network coverage, it is imperative to leverage all the available network technologies, e.g. terrestrial cellular, Satellite, short range wireless, etc. and for the 6G architecture to be able to encompass and integrate these different networks to provide a simplified and seamless experience to the users. The network service is expected to robust, resilient and truly ubiquitous which can be realized by leveraging multi-connectivity where applicable and required. The architecture should allow co-existence of a wide variety of networks, be it a macro network with a short-range, cell-free THz network, a Non-Terrestrial Network architecture (NTN).

Security: 6G connected devices are expected to become an essential part of life, e.g. for health and lifestyle improvements, management of tasks at home or in critical industries. This also implies an increased impact of security and privacy breaches in such a network. Hence, security, trustworthiness and privacy are going to be the fundamental tenets in designing 6G systems.

Cloud platform: In line with the trend towards cloudification of networks, the architecture should provide for a common orchestration framework across cloud platforms and network functions, The cloud platform may need to provide specific abstractions, e.g. to account for specialized hardware accelerators needed for radio functions in the Radio Access Network part. The cloud platforms are expected to migrate from specialized telco cloud platforms to generic public, private, or hybrid clouds. The locations can be on-premises, or in a central site. Multi-domain cloud architectures that span across operator, administration and trust boundaries will need to be considered.

Programmability: Future network and platforms should be developed in a way that is appealing and relevant to the ecosystem of software developers and application providers. This will demand a new level of programmability, such as Programming Protocol-independent Packet Processors (P4), that are independent of the hardware or the cloud platform the network is implemented on. Open and service-based interfaces, modular system design will allow easy integration of services from multiple vendors. This will allow optimal network deployments with only those functions that are considered essential for the use case while avoiding the overhead of instantiating and maintaining the non-essential one's.

Simplification and sustainability: As the network is expected to provide more and more capabilities, obviously the complexity of managing such a network also increases. In fact, this complexity and number of functions in the system have grown over the past generations. The introduction of 6G offers the opportunity to refactor the network functions to minimize the complexity and also leverage advanced software based approaches like the service-based interfaces (SBI) for different network functions to evolve and be deployed with minimal dependencies. SBI for the core has already been introduced as part of 5G. As part of 6G architecture and design, analysis of applicability of the SBI for the control plane between the radio access network and the core network should be undertaken. In addition, to simplify signaling procedures concepts like distributed Non-Access-Stratum (NAS) interface can be considered. Flexibility in function placement will also help to achieve sustainability

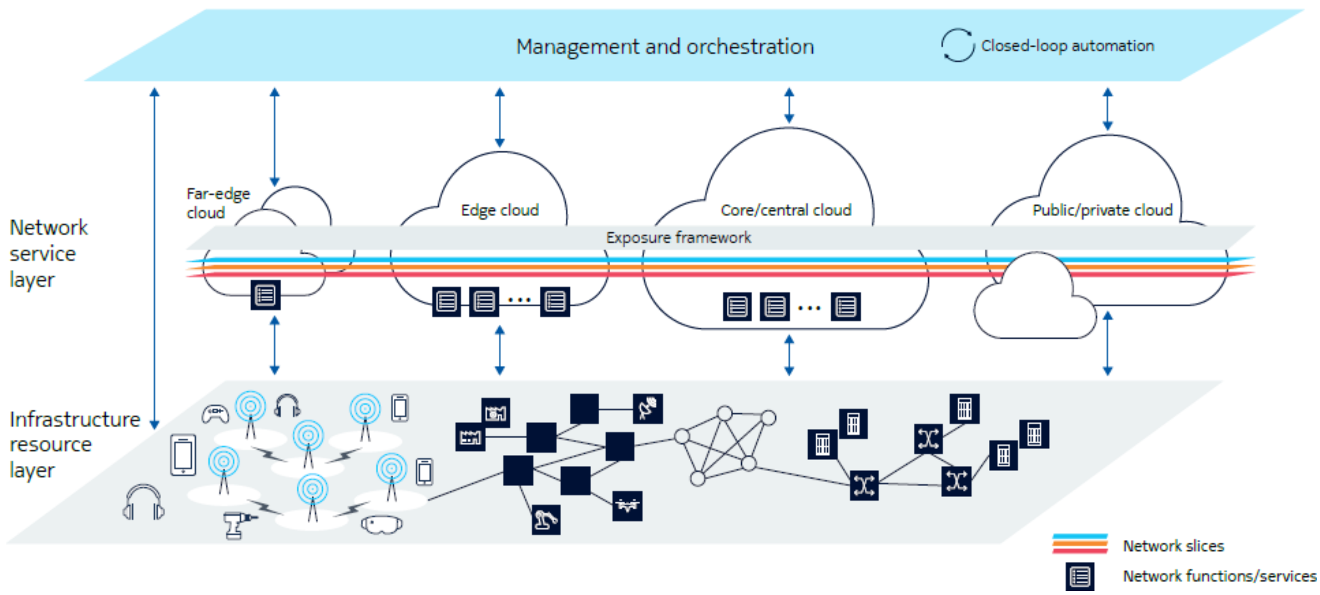

Fig. 5 End-to-end 6G architecture overview.

goals by reducing the amount of signaling and energy consumption. All aspects of 6G design should have "sustainability" as a central tenet.

Artificial intelligence and machine learning technologies are expected to be an integral part to power automation and optimization of the network, as well as in increasing the security of the system. This demands incorporation of functions and interfaces for large-scale data collection, processing and distribution, training for model refinement, and updating inference models within functions.

4.2 Architecture Overview

Figure 5 shows the envisioned architecture for 6G. The infrastructure resource layer including all the switches, routers, transport links, data centers, could infrastructure and radio equipment, including non-virtualized radio functions like Radio Unit (RU), Distributed Unit (DU) and the base stations, provides the physical resources to host the network functions and services. The network service layer is expected to be fully multi-vendor and heterogenous cloud-based. The far edge will serve a wide variety of devices — from IoT to smart phones to Industrial robots and machines. An exposure framework enables seamless interoperation and networking across multiple clouds. Network functions, operations and applications are implemented as services that enable the architecture to be softwarized, intelligent and efficient. This allows easy support for a wide range of applications specific QoS and QoE by providing the communication and computation services as programmable APIs that can be mashed up to create desired and specialized network instantiations.

The management and orchestration domain, evolves towards increasing the levels of automation and utilizing fully automated closed-loop control with augmentation via adoption of AI/ML technologies.

5. Technical Enablers

For the target use cases explored in Sect. 3, several technical enablers have been identified by Hexa-X for each research domain (Radio Access Network, Intelligent Network, Flexible Network, Efficient Network and Service Management).

Radio Access Network: High data rate radio links and distributed large MIMO are being investigated extensively to support the peak data rate up to 1 Tbps over the operational carrier frequency up to 300 GHz range. For the target higher frequency range, candidate waveforms, transceiver and receiver architectures are also studied in academia and industry [26]–[28]. These are deemed as essential for enabling e.g. massive twins and telepresence. In addition, radio-based localization is expected to provide a finer location from a device in 3D (horizontal plane and altitude) [29]. Sensing is a key enabler for 6G to detect events and changes in environments which has yet to be supported by the legacy generations [30].

Intelligent Network: Network automation has been a challenging issue to tackle the complexity in operating and managing networks as studied from the legacy generations. Likewise, support of network automation is essential for 6G and further targeted to enable zero-touch network (i.e. no human intervention) [31]. AI and AI as a Service are needed for most of the use cases, and most prominently indispensable for implementing the use cases for sustainability. AI utilization will also provide capability to place network functions in different processing points across the network fabric (aka dynamic function placement) for use case specific. UE/network programmability is also expected to

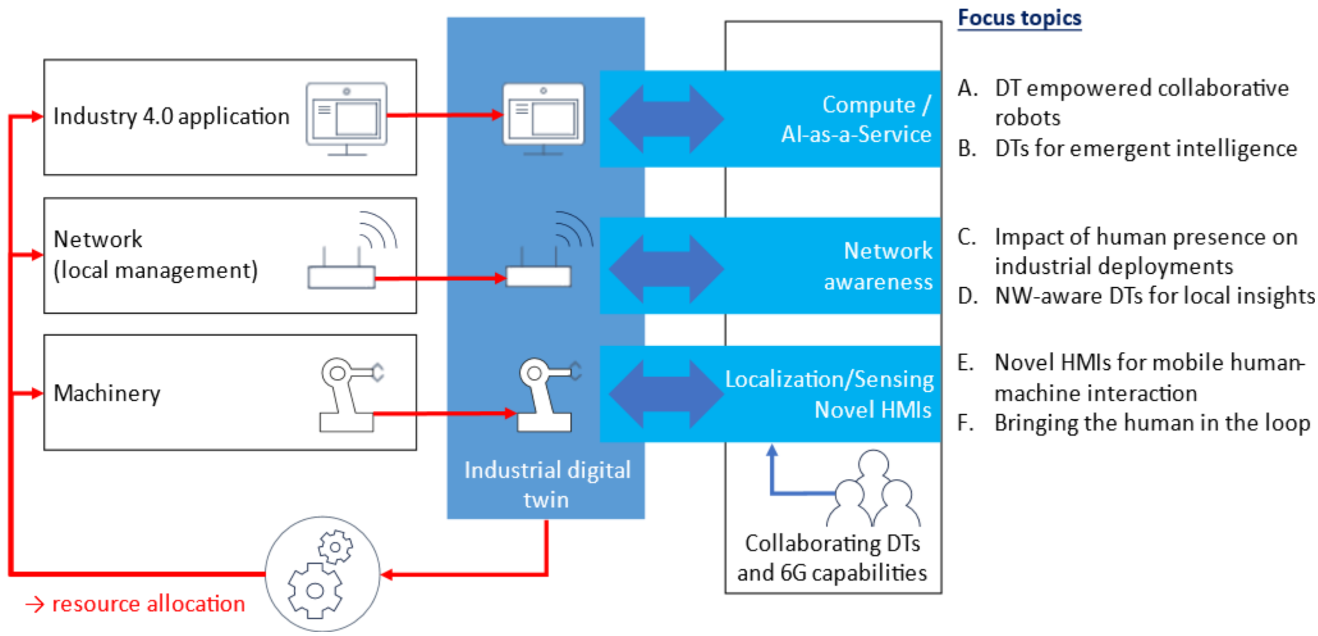

Fig. 6 Technical enablers for digital twins with HMI.

offer flexible 6G capabilities tailored for specific use case without depending on hardware capabilities.

Flexible Network: For 6G to offer the variety of services, network needs to be flexibly organized and tailored for each use case. One of the viable enablers is campus network which are networks of LANs in specific areas and used by industry, municipalities or educational institutions. The 6G use case will open the way to 3D campus networks covering aerial platforms, e.g. UAV (Uncrewed Aerial Vehicle), HAPS (High Altitude Platform Station). Mesh network, device-to-device communication and edge cloud integration are expected to be a key enabler to provide the flexible network, such as the campus network. Mobility is also a key enabler to support heterogeneous access to the flexible and tailored network for each service.

Efficient Network: Cloud transformation of businesses, services, and networks is a strong trend that is likely to continue in 6G. Whilst 5G core network has already supports cloud-native implementation of the Service-Based Architecture (SBA), full-fledged transformation towards cloud and service-based architecture is envisaged for 6G, encompassing Radio Access Network. Compute as a Service will also enable to offer computing nodes/resources for service basis.

Service Management: Management and orchestration require cross-domain optimization and collaboration due to the growing heterogeneity and complexity of the network. AI-driven approach and continuum management are key technologies in handling the overall resource coordination and management.

5.1 Enablers for Digital Twins with HMI

For the use case of digital twins with HMI described in Sect. 3.1, Hexa-X has been studying the technical enablers [21]. The current focusing topics and intermediate solutions are summarized as illustrated in Fig. 6.

A. Digital Twin Empowered Collaborative Robots

One of the potential directions for new industrial revolution, such as Industry 4.0 is that (mobile) robots can be autonomous, semi-autonomous or entirely tele-controlled and help humans in many different applications [32]. This solution direction is so-called "collaborative robots". Traditionally, industrial robots have been programmed offline, i.e., prior to robot operation: hence, resulting programs could not take human actions into account, leading to an overall poor flexibility of robot intervention. With collaborative robots, though, programming can become an online, synchronous, operation, which can lead to more powerful, human-aware programs. To support the on-line programming, one approach being studied is on a concept application scenario that strongly relies on XR technology and telepresence solutions, where two humans operating from remote sites need to cooperate to program a pick-and-place task on a collaborative robot.

B. Digital Twins for Emergent Intelligence

Emergent Intelligent (EI) considers intelligence of animals, including humans, as an emergent behaviour, i.e., it is spontaneously originated from a large number of complexly interconnected and interacting simple units. For example, human intelligence originates from the brain that consists of massive number of interconnected simple neuron cells. Another typical example is the collection intelligence of gregarious insects such as ants and bees, which have only very simple behaving patterns with every individual, while exhibiting well developed intelligence as colonies.

EI exhibits several features that benefit 6G applications, such as low computational complexity, minimized latency, etc. Nevertheless, EI generally requires a huge number of nodes participating in the networked system. Further than the capacity of user access, EI also requires reliable and timely communication to support efficient interaction between different agents. One promising solution to address this issue for EI is to deploy massive twinning. As the real-time status (raw knowledge), context information (abstracted/extracted knowledge) and semantic model (reasoning-level knowledge) of a physical object can be stored, analysed, and maintained at its digital twin, the decision engine of an EI agent can also be migrated from the physical device to its digital twin. Thus, the information exchange between different agents can be shifted from the physical radio environment to the cyber world. Every physical agent only needs to communicate with the cloud server where its digital twin is maintained, to upload its latest status and receive the decision made on the cloud. Thus, the massive radio signalling overhead can be mitigated, which significantly improves the radio resource efficiency and reduces the latency.

C. Impact of Human Presence on Industrial Deployments

Wireless communication with URLLC (Ultra Reliable Low Latency Communication) is paving the way for factory automation in Industry 4.0. The dominant traffic in these industrial environments is expected to be machine-to-machine traffic. Guaranteeing deterministic low-latency communication across the entire factory floor requires accurate modelling of rare failure events so that their impact during operation is understood and can be limited. In other words, we need to minimize the overall randomness in the system so that errors between models and measurements are minimal.

This is possible with future factories that are semi-controlled environments where accurate position information for mobile UEs such as AGVs (Automated Guided Vehicle) is available. The exact location of fixed machinery is also known. We can also expect accurate prior knowledge of the UE characteristics and capabilities such as antenna beam patterns, and number of antennas and their locations and orientations on the device. With location information and knowledge of the propagation environment (shape of obstacles in the environment and their materials as well as the impact of these obstacles on radio propagation), one can therefore model the radio condition between the UEs and the network using a digital twin. Given a model of the factory floor and the locations of the UEs and the network nodes, the digital twin could use sophisticated ray- tracing algorithms or electromagnetic solvers, or rely on a data-driven approach, or use a hybrid of both methods to predict the link conditions between the UEs and the network.

Without human presence, an industry 4.0 environment can be made rather predictable. For example, the UE mobility can often be planned fully in advance and modelled in digital twin (for example when the UE is attached to AGV or robot). The digital twin could be used to evaluate the radio conditions between the network and the UE and proactively plan UE locations to avoid outages.

D. Network-Aware Digital Twins for Local Insights

In Industry 4.0 scenarios, utilization of digital twins focuses on capturing the industrial processes as well as the state of machines (or parts thereof) and goods that interact as part of these processes, referred to as an industrial digital twin. Whilst wireless and mobile communication systems make a truly flexible Industry 4.0 scenario possible, with mobile machinery, AGVs, and robots it is important to know where all equipment is actually located, both for planning and efficient, secure, and safe operation as well as for monitoring of the environments. Therefore, respective exposure interfaces providing local insights into the network for industrial digital twins are required. One parameter for such an exposure framework is localisation and sensing information offered as a new capability in 6G systems. This information reflects the current setup and status of a certain environment and is one of the key information for a digital twin in an industrial scenario. Especially sensing features will pose totally new opportunities to monitor the surrounding and ongoings in a certain environment. From factories to hospitals or public events, understanding how humans, or machineries act will be the base for most decision processes.

E. Novel HMIs for Mobile Human-Machine Interaction

6G is supposed to provide ubiquitous connectivity of ultra-high density with low latency. This is paving the road towards a massive twinning scenario, where numerous physical entities are not only connected with each other by the pervasive Internet of Everything, but also synchronized with their corresponding digital twins, respectively. The coupling between the physical world and the cyber world is becoming tighter and smoother than ever before.

However, there is still one vertex missing from the triangle that completes the 6G vision of Hexa-X: the human world. To complete this ultimate gestalt of 6G network that joins three worlds, a seamless docking between the human world and the physical world, as well as between the human world and the cyber world, must be introduced as the last piece of puzzle. Such a task demands solutions for human-context-awareness, immersive Mixed Reality (MR), and accompanying digital twins, which cannot be sufficiently fulfilled by the conventional user interfaces mainly based on mouse-keyboard-screen and audio devices. Innovative human-machine interfaces are therefore called for to empower mobile human-machine and human-

CPE (Cyber-Physical Environment) interaction in the next decade.

F. Bringing the Human in the Loop

Digital twin systems must adapt to any new conditions and situations occur in real world, leveraging on extremely reliable low latency and high throughput networks, in order to succeed real-time digital/virtual representation. However, keeping the human in the loop for control of, and decision making on, robotic systems is still essential for various reasons such as complexity of systems or even legal constraints. Human-robot interactions are mostly limited to the labs and expert operators, with difficult interfaces that make them unusable for most non-skilled users. Humans should interact with the system in an intuitive and easy way, without being overwhelmed with unnecessary data and actions. Thus, appropriate user-centred designs have to be analysed and tested for human in the loop interactions.

To support this, the massive twining with multiple robots and sensors is being investigated. An HMI via desktop or VR application is developed to monitor, supervise, teleoperate the robots and solve any problems that may occur. Specifically, a user is able to start, stop, control and move the robots and robotic arms, view images or videos from robot onboard cameras and static cameras inside the environment and so on.

6. Conclusion

This paper navigated the target use cases envisioned for the 6G era. The architectural transformation and potential technical enablers were highlighted. In fact, the research activities on presented technical enablers and architectural concept are on-going, as well as Proof of Concept (PoC). For the technical topics presented in this paper, the authors like to encourage joint research and PoC collaboration with Japanese industry, academia and research initiatives such as Beyond 5G Promotion Consortium across the various industrial domains. The authors hope that the global collaboration with Japanese industry and academia will strengthen the alignment of 6G vision to produce harmonized 6G standards in future.

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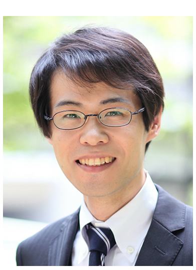

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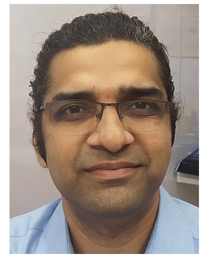

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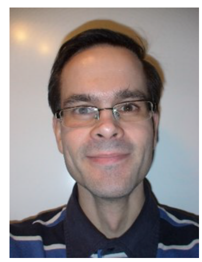

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