The Journey Towards 6G: A Digital and Societal Revolution in the Making

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I. Introduction

The rollout of fifth generation (5G) wireless networks continues across the world and is bringing a technological breakthrough with respect to previous communication networks. Another substantial development is currently taking place through beyond 5G (B5G) systems, where the focus is shifting from rate-centric enhanced mobile broadband (eMBB) services to ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC). However, with the emerging revolutionary changes in individuals' trends and the need to address existing societal challenges such as the digital divide and advancing healthcare, education, environmental sustainability, disaster management, etc., it is arguable whether the capabilities of beyond 5G (B5G) systems will keep up the pace with the market demands of 2030, which is expected to witness a new breed of Internet-of-Everything (IoE) services and radical advancements in human-machine interaction technologies [1].

Supporting cutting-edge future services not only necessitates delivering ultra-high reliability, extremely high data rates, and ultra-low latency, but also requires a new wave of network design, where computing, control, and communication are integrated into a network fabric that offers functionalities beyond communications, such as spatial and timing data. Researchers speculate that this grand vision will push fifth generation (5G) systems toward their limits within 10 years of their launch and calls for the conceptualization of sixth generation (6G) systems, envisioned to introduce disruptive technologies and innovative network architectures that govern the evolution from connected everything to connected intelligence [1].

In this article, unlike existing works, which generally adopt a classic fashion in discussing sixth generation (6G) systems requirements, challenges, and enabling technologies, we outline the vision of a 6G-powered world by shedding light on what 6G promises in Sec. II and overviewing the use cases (UC) that are expected to drive a digital and societal revolution in Sec. II. This is followed by introducing the paradigm shifts that formulate an evolved network architecture in Sec. IV. In Sec. V, we highlight the main 6G technologies needed to realize the vision of a future connected cyber-physical world. Finally, Sec. VI focuses on the recently envisioned Internet-of-Musical Things (IoMusT) [2] to depict how the discussed use cases (UCs) and technological paradigms can realize this ecosystem.

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II. What Does 6G Promise?

As the 5G is gaining ground, the research community has shifted towards laying the fundamentals of next-generation (NG) systems. The 6G vision is to create a seamless reality where the physical and digital worlds, so far separated, are converged. This will enable seamless movement in a cyber-physical continuum of a connected physical world of senses, actions, and experiences, and its programmable digital representation. With this futuristic converged reality, new ways to work remotely, meet new people, and experience foreign cultures and places will be made possible [3]. In addition, the vision of 6G is also to create more human-friendly, sustainable, and efficient communities. This requires networks that guarantee worldwide digital inclusion to support a wide range of elements, end-to-end (E2E) life-cycle tracking to reduce waste and automate recycling, resource-efficient connected agriculture, universal access to digital healthcare, etc [3].

Achieving the above demands establishing a ubiquitous networking infrastructure where each node within this network exploits intelligence to assess channel conditions and quality-of-service (QoS) specifications at other nodes so that network selection, whether fourth generation (4G) cellular, wireless LAN, Bluetooth, ultra-wideband (UWB), WiFi, satellite communications, or others, would be determined by the specific use case and network availability. This requires designing one unified 6G standard that provisions the convergence of the aforementioned existing wireless technologies, enabling seamless and massive connectivity across sensors, people, and things, meaning that 6G will leverage the substantial infrastructure already deployed by previous wireless generations and concurrently embrace emerging technologies, like artificial intelligence (AI)/machine learning (ML), high-frequency communications, quantum communications (QC), and quantum machine learning (QML), to offer new services.

Such integration will require standardization bodies to define interfaces and key performance indicators (KPIs) to seamlessly support this 6G vision. The International Telecommunication Union (ITU)'s radio communication division (ITU-R) has been working with governments and industries to develop the requirements and specification of mobile communication systems. Following the release of International Mobile Telecommunications (IMT)-2020 (5G), they are now moving towards IMT-2030 (6G), which is the initial step towards establishing a unified global standard for 6G technology [4].

In this context, ITU-R had identified 8 KPIs for IMT-2020, i.e. the connection density, network energy efficiency, area traffic capacity, peak data rate, user experienced data rate, latency, spectrum efficiency, and mobility. However, it is expected that these indicators will not be sufficient to address the disruptive use cases and applications expected in 6G and beyond. While the 8 KPIs used for assessing 5G are still applicable to 6G, their values need to be updated to reflect technological advancements and the emergence of new applications. Additionally, new indicators are necessary to evaluate new services in 6G, such as positioning, sensing, security, and intelligence. To this end, various organizations and scholars have proposed a combination of quantitative and qualitative KPIs, such as the sensing/imaging resolution, the positioning, and the battery life (of Internet-of-Things (IoT) devices) [4]. A comprehensive review of proposed 5G and 6G KPIs can be found in [5].

TABLE I
OVERVIEW OF DRIVING UCS DEFINED FOR NEXT GENERATION COMMUNICATION SYSTEMS

Organization	Identified UCs/UC families
3GPP	- Integrated Sensing and Communication - Ambient Power–Enabled IoT - Localized Mobile Metaverse Services - AI/ML Model Transfer
5GPPP	- Augmented reality for sport events - Real-time digital twins in manufacturing - Patient monitoring with in-body and wearable sensors - Human and robot co-working - Tracking of goods and real-time inventory - Electronic labelling - Augmented reality for professional applications - Wander detection and patient finding - Contact tracing and people tracking in large venues - Position tracking of robots and unmanned vehicles Location-based information transfer - Virtual reality home gaming - Smart home automation
NGMN	- Enhanced Human Communication Enhanced Machine Communication - Enabling Services - Network Evolution
ITU	- Immersive Communication - Hyper-Reliable and Low-Latency Communication - Massive Communication - Ubiquitous Connectivity - Integrated Artificial Intelligence and Communication - Integrated Sensing and Communication
Hexa-X	- Enabling sustainability - Massive twinning - From robots to cobots - Hyperconnected resilient network infrastructures - Trusted embedded networks - Enabling services harnessing new capabilities

III. DRIVING TRENDS AND USE CASES

Being at the beginning of the 6G research and development (R&D) journey, all players in of the ecosystem are actively proposing novel promising UCs that will help define the relevant KPIs and promising technologies for the era. To this end, over and above academic efforts, several organizations, including standardization bodies (e.g. 3rd Generation Partnership Project (3GPP)), associations (e.g. 5G Infrastructure Public Private Partnership (5GPPP), Project REINDEER), forums (e.g. Next Generation Mobile Networks Alliance (NGMN)), agencies (e.g. ITU), and even consortiums (e.g. Hexa-X), have begun investigating 6G UCs to lay the foundation for next generation communication systems. Table I provides an overview of the UC proposed by active important organizations leading the R&D and standardization efforts of next generation communications systems. Building on this plethora of UCs, we propose four driving UC clusters, which both lay the foundation for numerous applications and set the technical requirements for future communication systems.

A. Internet-of-Senses (IoS): Any sense for anyone?

The essence of the IoS, coined by Ericsson [6], is built on delivering multisensory experiences over the networks. This UC allows humans to have digital sensory immersive experiences that replicate or even augment what we experience in the physical world through visual, auditory, haptic, olfactory, and gustatory stimuli. This opens the door for an unprecedented opportunity to blend those multisensory experiences with our local surroundings and interact with people, devices, and robots remotely and in real time, without any location boundaries. The IoS is envisioned to be manifested through many revolutionary interactions, such as immersive communication, five senses merged reality, all senses online shopping, remote operation of machinery, Venn rooms, and sustainable vacations in virtual reality to name a few.

B. Digitalized and Programmable Physical World

The tremendous growth in connected IoT, which is based on the real-time exchange of data generated from billions of embedded sensors and actuators, creates the fabric for the digital representation of the physical world. Leveraging this lays forward the foundation for having every imaginable object connected and digitally interactive in many activities and processes across industries and society at large. This also allows each physical action to be controlled and programmed according to detailed planning and execution of activities. In future, further digitalization will become possible through the emergence of new materials, such as metal oxides, polymers, etc., and sensor technologies, such as nano electro mechanical systems (NEMS) enabling smart dust [7].

C. Connected Intelligent Machines

The emergence of a new breed of data traffic is yet another aspect revolutionizing NG networks. Specifically, so far, networks were designed to mainly serve people, and thus only interact with human intellect. Meanwhile, future mobile networks will be able to communicate with various intelligent entities, such as AI-powered intelligent machines, and ultimately enable widespread intelligence, where humans and robots interact with each other to solve complicated tasks. This will blur the line between humans and intelligent machines. Such transition will inevitably have impacts on the network design and requirements [3].

TABLE II
6G USE CASES, KEY COMPONENTS, AND STEPPING STONES TO ADDRESS SOCIETAL CHALLENGES

Use Case	Key Components	Stepping Stone	Innovative Features & Potential Application Scenarios to Address Societal Challenges
Internet-of-Senses (IoS)	Next-generation devices, sensing, and actuation	Touch and motion	• Haptic gloves and body suits with mechanical actuators/Synthetic skin as a thin vibrating actuator for touch feedback. • Electric tactile displays for tactile feedback on any surface, including textiles. **Application Scenario**: virtual and remote rehabilitation and therapies in **healthcare**. • Bands with Electromyography (EMG) sensors for detecting muscle activity and arm movement. **Application Scenario**: controlling a drone with an EMG armband during **disaster management** scenarios.
		Networked XR glasses	Standalone XR glasses with integrated processing and 5G capabilities/ Ultrathin form factors/ retinal hologram projectors. **Application Scenario**: immersive **education** experience anytime and anywhere.
		Taste and smell actuators	• Taste display (lickable screen) using electrophoresis to generate base tastes. • Smell actuators: devices producing scents in response to digital signals and implants stimulating nerves. **Application Scenario**: smart food tasting and smell detection to enable consumers to assess the freshness of food before purchasing and providing early detection of spoilage, contributing to **environmental sustainability**.
		Brain-computer interfaces (BCIs)	• BCI-enabled XR glasses for enhanced user interface (UI) in place of touch screens. • Optical hand tracking and eye-tracking for UI interaction. **Application Scenario:** efficiency and safety enhancements in **Industry 4.0** by providing operators with hands-free access to information, data processing capabilities, and real-time alerts for adherence to safety protocols.
	Multi-sensory communication	Shared audiovisual and haptic digital objects	• Audiovisual digital objects are AR overlays in still environments with occlusion and local rendering. • Tactile digital objects in AR that can be manipulated, picked up, used and moved. • Holographic communication utilizes spatial audio techniques to create a realistic sense of sound directionality, while shared AR experiences rely on real-time rendering to generate and display AR content synchronously for remote users. **Application Scenario: d**igital inclusion in workplaces to bridge the **digital divide** by providing equal opportunities to access online training materials and enable immersive and interactive remote communication and collaboration.
	Algorithms for the IoS	Network-aware rending	Algorithms will adapt to network conditions and available resources, compensating for imperfections, to achieve high-quality remote user experiences.
		Complete sensory modeling	Algorithms will model human and environmental senses, enabling realistic and real-time information extraction from fewer low-cost sensor inputs.
	Trustworthy IoS	Consent management	Users can control data recording by utilizing gesture and sensory recognition for consent, ensuring privacy through differential privacy methods and third-party data management
		Explainable AI for IoS	A framework incorporating bias detection, AI explainability, and policy enforcement is needed for sensory data in IoS, ensuring privacy, transparency and user-defined guidelines.
Intelligent Connected Machines	Intelligent machines (IM)	Regenerative self-managed machines	Through the application of CL, machines can retrain AI models, choose their own architecture, handle software life cycle management, and improve interaction in social and physical contexts. **Application Scenario**: in **disaster situations**, search and rescue robots with CL capabilities continuously adapt AI models, improving performance in hazardous environments, locating survivors, and aiding rescue teams.
		Machines learning from each other	Machines enable skill sharing, recognizing and offering useful skills to other machines, determining relevance for unique problems, and facilitating ad-hoc training through transfer and social learning in multi-agent systems. **Application Scenario**: in **healthcare**, medical robots with skill sharing capabilities collaborate to address unique patient problems and enhance healthcare delivery.
	Interoperability	Interoperability across systems	Common data models enable diverse devices to describe, interpret, analyze, and share data, fostering universal system interoperability across ecosystems, facilitating seamless interaction between any systems. **Application Scenario**: common data models in music **education** common enable diverse devices to describe, interpret, analyze, and share musical data, allowing seamless interaction between instruments, software, and educational platforms for enhanced experiences.
	Human-machine co-existence	New ways of interactions	Humans interact with machines through natural language, gestures, AR/VR, intents, and body-machine interfaces (e.g., implants), such as robot learning from demonstration, training robots/digital twins with sensors, AI, AR/VR, and BCIs. **Application Scenario**: to bridge the **digital divide**, interactive machines can empower underserved populations through natural language, gestures, and body-machine interfaces, facilitated by robot learning and sensor-based technologies.
	Systems of systems	Dynamic membership to systems of systems	Dynamic membership allows the creation and updating of open systems of systems, where individual systems can connect and collectively provide functionality, incorporating neighboring and emerging systems, such as a self-driving truck transitioning between different factory systems. **Application Scenario**: dynamic membership enables seamless collaboration and adaptability in autonomous **industry** applications, improving efficiency in tasks like automated assembly lines and autonomous warehouses.
	Trustworthy intelligent machines	Accountable and responsible (IM)	Machines as legal entities are held accountable through mechanisms ensuring responsibility and ethical trade-offs in intelligent systems, promoting human-machine interaction, and identifying acceptable outcomes. **Application Scenario**: in **healthcare**, machines in autonomous surgical systems take responsibility for surgical procedures, ensuring adherence to ethical standards and providing transparency in decision-making, ultimately enhancing patient safety and outcomes.
	Enhanced network platform features	Enablers for native AI communications	Emerging AI-type communications among connected intelligent machines necessitates network requirements accommodating spiking neural networks, attention-based multicast, and federated learning, while enabling programmability and AI-designed protocol stacks for optimized communication.
Digitalized and Programmable Physical World	Fully programmable and automated world	Universal orchestration and reprogramming	Universal orchestration and programming of large complex systems enables integration across domains and system silos through new programming paradigms, systems of systems, large-scale distributed software systems, and software architectures. **Application Scenario**: optimizing the traffic flow within a **smart city** by controlling traffic lights, rail traffic, self-driving buses, and by monitoring pedestrian movements, etc.
		Programmable materials/4D printing	Programmable material includes reconfigurable metamaterials and 4D printing, enabling objects to change properties and form even after being produced, expanding possibilities in material science and manufacturing. **Application Scenario**: in **disaster management**, programmable material can be used to create adaptable emergency shelters, providing flexible and resilient spaces for displaced individuals.
	Seamless positioning and mapping everywhere and all the time	Ultra accurate, highly reliable, low-latency positioning and time	The 3GPP-based system ensures accurate positioning and synchronized time using a diverse set of procedures, signals, and measurements, including global navigation satellite system and standardized sensors, enabling precise location and time synchronization across devices and networks. **Application Scenario**: by providing accurate positioning and synchronized time to underserved areas, remote and marginalized communities can benefit from improved connectivity, enhanced **emergency response**, and access to location-based services, bridging the gap in **digital divide**.
	Embedded Sensing and actuation	Smart dust	Smart Dust comprises tiny devices that detect various stimuli and combine sensing, power, computing, and wireless communication in a small form factor. They are built from 3D printed materials, utilize novel materials, and are powered by the physical world for self-sustainability. **Application Scenario**: in the context of **smart cities**, smart dust may be used for precise monitoring of environmental factors in urban farming, optimizing resource usage and crop growth by making informed decisions regarding irrigation, fertilization, and pest control.
	Digital representation of everything	Collaborative digital twins of complex systems	Semantic interoperability allows digital twins of various systems to engage in peer-to-peer communication, collectively representing a broader physical reality.
	Network platform features for the digitalized world	Network storage fabric for digital representations and digital threads	Trustworthy edge storage is crucial for low-latency access to digital representations like digital twins and digital threads, potentially integrated into dedicated networks for advanced industrial use cases and IoT platforms. **Application Scenario**: by monitoring real-time data and running predictive models, DT can identify opportunities for energy conservation, waste reduction, and efficient transportation routes, aiding in the development of **sustainable practices** and policies for a greener future.
Connected Sustainable World	Responsible ICT	Expanding ethical frameworks	Incorporate ethical frameworks into policies for all emerging technologies. Efforts are needed to address ethical responsibilities beyond AI, including environmental protection and considerations for biodiversity and planetary boundaries. **Application Scenario**: in **education** systems, ethical frameworks for emerging technologies promote responsible technology use and **environmental consciousness** among students.
	Resource-efficient ICT	Climate optimized networks	Network activities can be optimized and prioritized based on power availability and climate impact. Integration with the energy grid, heat recovery, and visualization of energy consumption can enhance energy efficiency and operator optimization. **Application Scenario**: in **healthcare**, network activities can be prioritized to ensure critical medical devices, such as life-support systems or telemedicine platforms, receive uninterrupted power supply.

D. Connected Sustainable World

The focus on sustainable development is pushing governments and organizations to reconsider their regulations and operations to answer the populations' increasing concerns. In this context, the information and communication technology (ICT) sector has been in the spotlight both as an enabler for achieving the United Nations (UN) sustainable development goals (SDGs) [8] and as a substantial contributor to global carbon emissions. In fact, despite 5G's game-changing specifications, which achieved 10 times greater energy efficiency than 4G and enabled life-changing applications [1], it is undeniable that the full potential is not reached, where global connectivity and carbon neutrality are not a reality yet. Therefore, nowadays sustainable ICT efforts are broadly classified into sustainable ICT and ICT for sustainability. The former ensures that the ICT sector meets the sustainable development targets, and is concerned with the resource efficiency of the ICT sector as well as its impact on people, society, and the planet. Meanwhile, ICT for sustainability is centered around using the ICT sector as an enabler for sustainability, such as for inclusion, for the benefit of society, and for the environment.

Based on the four highlighted UCs, we envision that the realization of each of one of them over the coming decade will be a result of the development of key stepping stones as detailed in Table II.

IV. Architecture Evolution: A Formula for 6G!

Capitalizing on the discussed UCs and their requirements, in this section, we introduce six integrated architectural pillars for 6G, i.e. control, compute, cognition (3C) and densification, digitalization, distribution (3D). These pillars are presented in Fig.1, and are discussed in details in what follows.

A. Control

The complexity brought on by 5G, IoT, and the increase in the number of connected devices have pushed for virtualization of physical networks. New software-defined capabilities, including service assurance, orchestration, analytics, and data-centric processing, were brought on by this virtualization. This brings substantial benefits but also a great deal of complexity for managing and maintaining the network. In this context, it is clear that we need to step away from human-driven networks towards automation, which is essential for achieving streamlined services and operations, rock-solid reliability, and keeping businesses and users satisfied. Control systems are therefore now considered a pillar of B5G networks, where special attention has been given to closed-loop automation [9]. Closed-loop automation monitors and analyses network occurrences like failures and congestion using data and analytics, and then takes appropriate actions to resolve any issues. The term "loop" refers to the communication feedback loop between the network's performance being tracked, identified, adjusted, and optimized to allow for self-optimization.

Closed loops have been around and employed in control systems for a while. However, the idea of having many closed loops operating at once and interfering with one another is relatively new. This is particularly the case in autonomous communication networks, where this interference has to be identified and dealt with. In fact, numerous control loops are needed in order to optimize global networks and E2E services. In this context, automatic conflict resolution, i.e. mechanisms to resolve conflicts between competing intents or closed loops autonomously are needed. As the network automation scale grows, certain control agents' goals will compete with one another, and there may be instances where several control loops are directed at the same controlled elements. In order to achieve the optimal trade-off between competing goals and achieve network and service management goals in B5G networks, effective tools to resolve such conflicts are needed.

B. Compute

As discussed in Sec. III-B, it is expected that 6G UCs will widely rely on distributed ubiquitous sensing and actuation, which can be of diverse and new generations of modalities, leading the data processing to be highly distributed in tiers of different capabilities and include inferencing, ML, sensor fusion, and sensing-actuation control loops to automate simple or richer tasks locally, all based on multi-modalities. A number of UCs will depend on brain-computer interfaces (BCI), meaning that, when interfacing directly with the brain, advanced algorithms will be needed to transform the signals from the brain to data that is meaningful to computers and vice versa. For example, enabling machines that sense and predict our future actions and desires requires advanced computation technologies empowered by prediction analysis, intent-based techniques of ML (i.e. ML that anticipate human intents), BCI that can access our thoughts, emotions, and memories. Additionally, 6G UCs are driven by a massive number of data and will, therefore, need massive computing power to infuse sensor data of real-world content into merged virtual reality. In dynamic environments, extremely low latency computation for dynamic object detection, tracking, and rendering is required to generate high-resolution spatial maps/moving object models.

It is envisioned that the network compute fabric will be distributed in nature and will extend all the way to even the tiniest devices, making these devices part of the fabric, termed "*mist computing*" [10]. *Mist computing* is expected to be carried out at the extreme edge of the network in tiny devices, such as microcontrollers and sensors, and use computing power on sensors to process, precondition, and optimize data before its transmission. This renders the processed data more compact and results in communication power savings. In this extended network compute, data, and storage (CDS) fabric, compute and storage always happen at the most optimal location in the entire system. Data and computing can also dynamically move or be distributed over different locations. The unified distributed CDS fabric created might lead to rethinking the architecture of the conventional IoT platform into a distributed fabric-native (or "mist-native") digital world "platform" consisting of tiny components distributed over the unified CDS fabric.

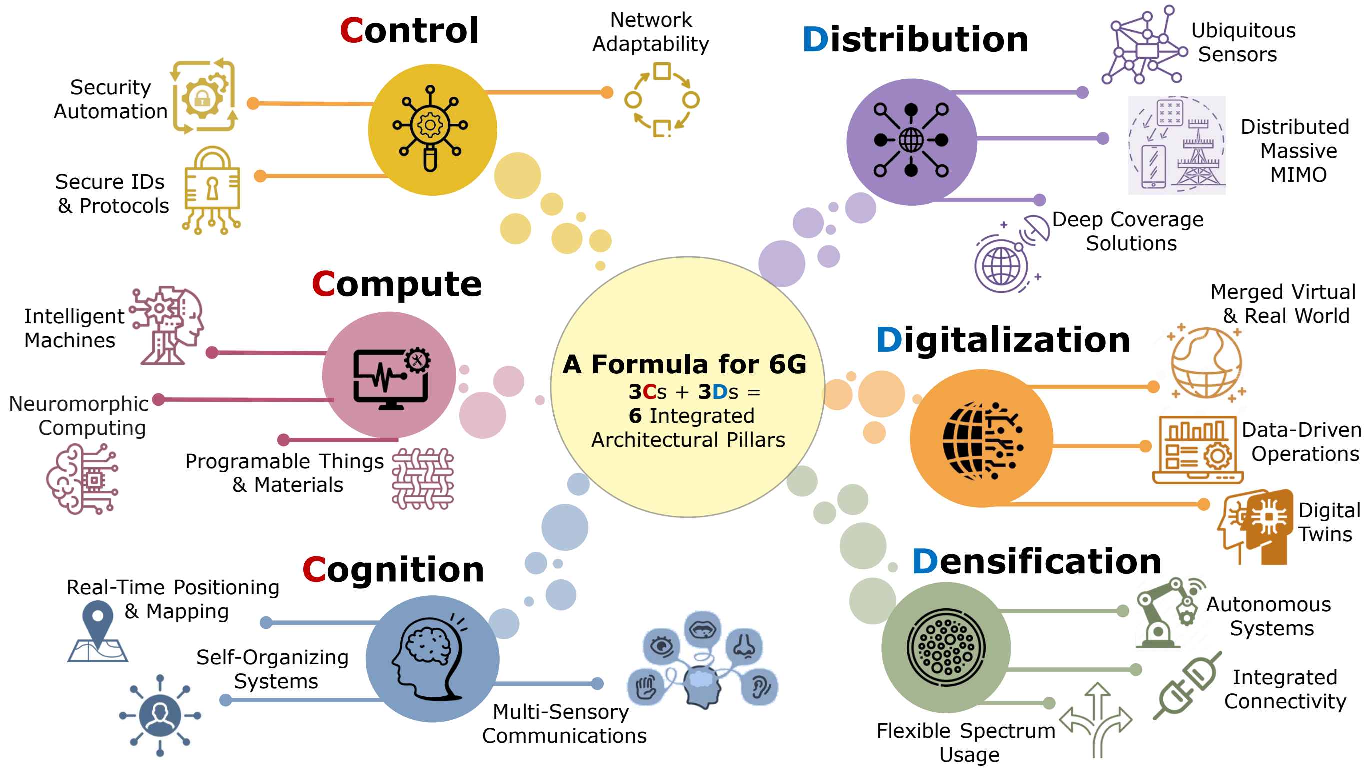

Fig. 1. 6G Architectural Pillars.

C. Cognition

As both communications and radio sensing systems are evolving towards higher frequency bands, miniaturization, and larger antenna arrays, they are becoming increasingly similar in terms of signal processing, hardware architecture, and channel characteristics. This opens unprecedented opportunities for offering ubiquitous learning and intelligence across the network by integrating sensing within the existing wireless infrastructure. In particular, achieving a cognitive, self-learning physical world will rely on self-generating digital twins (DT) of the planet, where almost everything can be programmed and repurposed, including physical materials [11]. While this entitles the deployment of data-driven network architectures, where relevant data can efficiently and securely be distributed and analyzed to optimize the network performance and operations, it also means that decisions should be made on data whose exposure and collection are configured intelligently on-the-fly. As such, we need tools that automate the selection of source data for model training in natively distributed ML algorithms.

The AI of the cognitive network might even be designing new services on the fly for machines based on their needs. The network could be seen as a large-scale distributed intelligent machine serving all other connected intelligent machines. From an architectural perspective, for the network to be an enabler of cognitive systems, it would require a large-scale of distributed intelligent machines that provide connectivity, computing, storage, mediation, and other services to all other intelligent machines [11]. It is, therefore, expected that ultimate cognition may be possible through the emergence of a connected global brain where the AI of the network interacts with the AIs present in all those multi-agent systems of systems (SoS) at a global scale, optimizing the operational aspects of the SoS. In this case, the network could also perform SoS governance and monitoring, including prediction, identification, and avoidance of unexpected emergent behaviors. This requires a shift from reactive to predictive management, which heavily depends on continuous learning (CL) for autonomous system operation, where humans can take more of a supervisory role. Once this happens, a structure for governance should be introduced to decide what autonomy the management system is trusted with and how it should interact with its human operators.

D. Densification

One of the communication networks KPIs that has notably evolved over the past decades is connection density, which quantifies the number of devices satisfying a target QoS per unit area. For instance, 5G is expected to support 1,000,000 devices per square kilometer for mMTC applications [1], while the connection density of 6G is expected to be at least an order of magnitude larger. Although not always in the spotlight, the connection density has significantly impacted the architecture of mobile networks. Indeed, increased connection density calls for higher spectrum efficiency, which has resulted in network densification through the deployment of increasingly smaller cells.

Network densification adds more sites in a given area to increase the network capacity. This can be achieved through sector splitting or the deployment of macro/small/indoor cells or by increasing the number of transmit/receive antennas. Network densification also lessens the effect of the high load on the hardware, which is not the case when spectrum modification is employed to satisfy the increasing connection density requirements. However, maximizing the efficiency, being the spectrum, energy, overhead, etc., of the network becomes increasingly complex with network densification. This is essential to enable cost-efficient deployment of very dense networks as well as to ensure the strict carbon neutrality targets discussed earlier.

To this end, dynamic and flexible deployment solutions will become a cornerstone of 6G networks. This is essential for ensuring future-proof cost-efficient and sustainable high-capacity and resilient networks necessary for NG UCs. In this context, heterogeneous nodes, including ad-hoc, user-deployed, mobile, and nonterrestrial ones, can be seamlessly integrated/removed to scale up/down the capacity. For instance, multi-hop deployment could enable cost-efficient on-demand or rural coverage.

E. Digitalization

Ubiquitous digitalization and programmability will be automatically available anywhere and anytime by levering advanced distributed ubiquitous sensing and actuation. This enables a future where we can create digital replicas, or otherwise "*DT*" [11] of everything we engage with in the real-world - like cities and their associated infrastructure and dynamics. DTs are expected to provide digital representations that may be accessible and controlled globally and simultaneously by a large number of individuals and applications, and will lay down the path toward detailed planning and execution of activities, as well as accurate management and optimization of large entities, such as buildings, roads, hospitals, etc.

Digital representation of everything is realizable through a number of cornerstones. More specifically, data structures and semantics of one physical entity should be harmonized and unified to allow for better utilization of the platforms to which DT connect and to be able to extract more meaningful insights on the overall physical system. Moreover, DT of all objects and places require evolved IoT platforms that make it possible to create DT of even the simplest objects. Hence, having uniform data structure and ontology allows aggregation of twins into twins of larger systems, i.e. "*massive twinning*", that facilitate semantic interoperability, where standards and AI allow exchange between different systems and domains in a meaningful way [12]. As such, systems that have not been jointly designed can extract the meaning of data from other systems. This is enabled by algorithms that can abstract meaning regardless of the information's representation format.

Collaborative DT of complex systems is a natural result of semantic interoperability, as the later enables DT of different systems to engage in peer-to-peer communications and jointly represent a larger portion of the physical reality. This in its turn opens the door for *twin mobility* where twins of physical entities that change context or location follow their physical counterpart both in 1) where DT reside, i.e., what compute and storage is used and 2) which DT they interact with to model a bigger piece of reality, e.g., mobile user equipment connected to different networks or base stations, or a human seeking medical care in different locations.

F. Distribution

Recent advancements in virtualization of radio access network (RAN) and core network functions facilitated the management of highly distributed networks and led to the shift towards distributed architectures. This trend is accelerating with the increasing requirements for lower latency, higher volumes of users, and higher data rates, which are motivating the deployment of distributed network and compute elements closer to the users in 5G. In 6G, the distribution trend is expected to expand significantly both to push the performance, as in previous generations, and as a result of the technological advances, particularly the increased device processing capabilities and advances in ML. Specifically, advances in sensing and actuation technologies, discussed in Sec. III-B, as well as the network densification and increased connection density presented in Sec. IV-D will set the ground for futuristic highly distributed architectures. Meanwhile, new ML and control paradigms, such as distributed learning and artificial collective intelligence (ACI), will enable the full potential of these distributed systems.

In NG networks, data storage and processing will therefore be highly distributed in layers with diverse processing capabilities, forming the network compute fabric. This architectural evolution will also affect the embedded intelligence in the applications and network. The traditional offline and centralized ML is going to shift towards online models that are natively distributed in the different networked tiers for decentralized decision making. Such distributed architectures will also affect the way applications are processed in the network. This will require new methods for achieving seamless synchronization, mechanisms to support the E2E performance guarantees of distributed applications, distributed data management and governance models, new efficient service-based interfaces, etc.

V. A Technological Perspective

In this section, we shed light on four key paradigms that are expected to shape the research focus on candidate innovative technologies that should be developed to facilitate the journey toward future network capabilities and NG UCs' requirements.

A. Limitless Connectivity

Emerging societal trends and applications relying on fully automated systems and intelligent services are validating the importance of telecommunication systems in delivering limitless connectivity [1]. This encompasses both performance and coverage, meaning that connectivity should be available to anyone, anytime, and anywhere, and that the QoS should satisfy the application/user requirements in order to bridge the digital divide in a sustainable manner. As such, a fundamental enabling technology is network adaptability, which refers to the idea of enabling rapid network deployments and the fast introduction of new services. This comprises dynamic network deployments, which include ad-hoc or temporal deployments and mobile and non-terrestrial network nodes, enabling cost-effective densification and limitless rural coverage.

In the context of densification and distribution, lean network design approaches aiming to reduce the overall network complexity, e.g. by limiting the number of interfaces and the amount of duplicated functionality, are essential. Finally, the 6G architecture has to be optimized for cloud deployments. In fact, the 5G RAN architecture is based on nodes connected by point-to-point interfaces, while the functional separation in the core was derived from pre-cloud legacy architectures [13]. Therefore, both RAN and core service-based architectures will need to be re-engineered to include service-based interfaces that enable higher levels of optimization. Services supporting the dynamic and adaptable network vision will also be needed, including network sharing, network evolution, migration, etc. For example, DT technology offers valuable capabilities for enhancing high-frequency communications. By utilizing multi-modal data from DT, system design can be optimized, allowing for testing and fine-tuning of parameters like antenna placement, transmission power, and modulation schemes. This optimization maximizes performance and coverage. Additionally, the DT's multi-modal data improves contextual awareness, enabling identification of active and idle users in the vicinity. This information aids in designing effective beamforming strategies, optimizing signal quality, and minimizing signal loss caused by blockage and interference [11].

B. Trustworthy Systems

Recently, we have witnessed mobile communications and networks shifting towards being a critical infrastructure supporting societies, industries, and consumers. As we move forward, network capabilities will evolve to the point where they can accommodate even the most mission- and business-critical UCs. This impels the need for secure, resilient, and privacy-preserving network platforms with proven satisfactory performance in challenging environments. All product lifecycle phases, including network development, deployment, and operation, must have built-in security automation and assurance capabilities [3].

The level of confidence in the accuracy with which an information system's security features, practices, processes, and architecture effectively mediate and enforce the security policy is known as security assurance. In the evolution towards 6G, several challenges are expected to arise. The most notable one is certainly the security, privacy, and trustworthiness of AI, which will be embedded in the network fabric. In fact, the security assurance of AI and ML is rather critical. Most often, AI is regarded as a black box, which makes it hard to explain and complicates the security assurance, which for now can only be assessed by testing the output of a model for a given input. To safely embed AI in critical applications and infrastructures, it is important to develop tools, processes, regulations, and benchmarks, to assess the security assurance of AI. This includes assessing that the training and inference data is kept confidential and preserves privacy, the model does not reveal confidential or privacy-sensitive information through inversion or reverse engineering of trained models, the model yields reliable and explainable outcomes, and the model and system integrity and robustness are maintained [14].

C. Cognitive Networks

To realize fully autonomous networks capable of supporting a wide spectrum of versatile services at no extra cost and complexity, it is crucial to raise the network intelligence level. This is expected to include two main aspects; 1) zero-touch deployment and operation and 2) continuous real-time performance improvements. This means that service and infrastructure configurations will no longer be handled manually.Instead, as discussed in Section IV-C, the network architecture will rely on distributed intelligence and CL to make intelligent choices on E2E service parameters. As discussed in Sec. IV-A, new mechanisms need to be developed to manage the interaction of multiple closed loops running simultaneously and automatically resolve any conflicts resulting from this interaction.

Similarly, new technologies for intent-based management should be deployed to allow human-network interaction [3]. To this end, human operators use high-level declarative languages to define system operational goals in the form of "*intents*, which are then translated to lower-level instructions (action plans and settings) using intelligence before they are applied in the network infrastructure. To realize this effectively, it is critical to develop cutting-edge reasoning, context awareness, and domain knowledge mechanisms capable of learning from the existing processed data and automatically making rational decisions and understanding how to apply an intent on different levels, e.g. domain, user, customer, application, operator, or country [15]. For example, in highly dynamic and complex networks, such as dense HetNets, a DT may acquire multi-dimensional information for enhanced awareness and cognition. This can be regarded as an all-senses base station capable of capturing multi-modal data, that can be leveraged to train AI models for improved inference, with reduced network overhead.

D. Network Compute Fabric

The emerging 6G UCs, discussed in Sec. II, require a pervasive network platform that tightly and effectively integrates the discussed six pillars formulating the 6G architecture. As such, for the network to act as one unified entity to satisfy the aforementioned pillars' requirements, innovative technologies should be developed to provision unification over ecosystems, execution environments, data platforms, and intelligent operations.

For the network compute fabric to be unified, it is anticipated that exposure and federation will happen across all the ecosystem partners including the network, application developers, cloud providers, operators, or device and equipment vendors [3], [1]. This means that exposure of integrated connectivity and computing to edge UCs and associated enablers will be required. Furthermore, standalone on-premise networks and edge cloud for digitalization of industry/enterprise are expected to be deployed in order to support real-time applications, keep data on-premise for security cost reasons, and

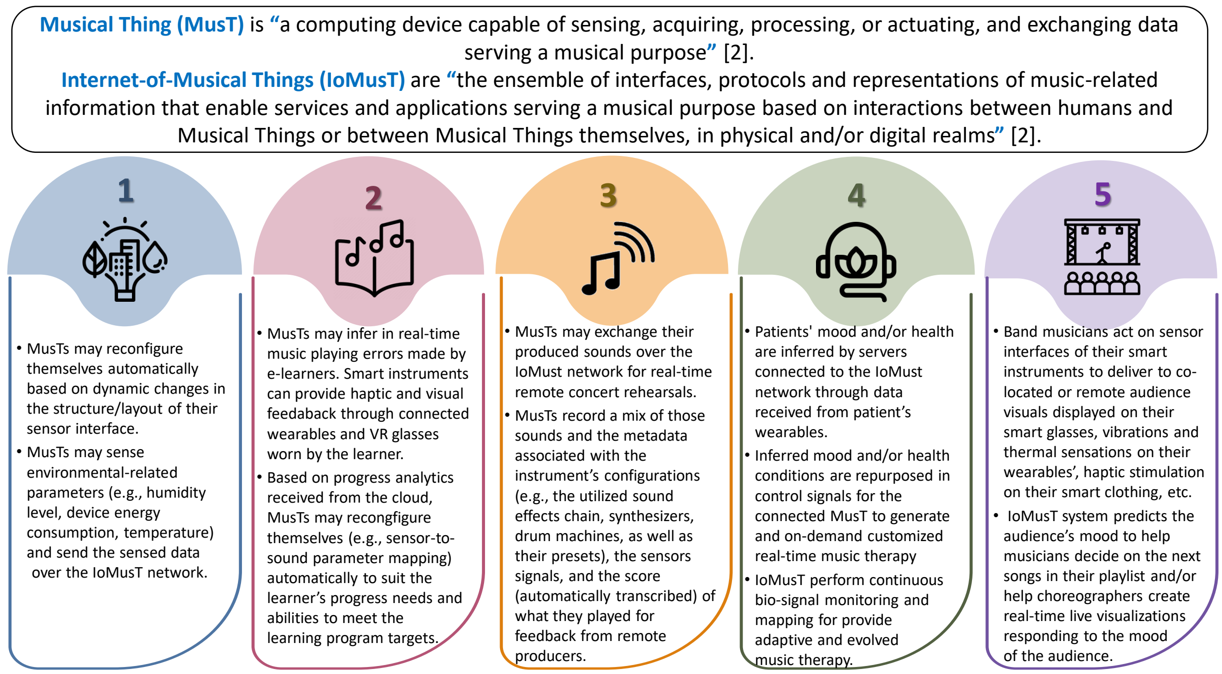

Fig. 2. Internet-of-Musical Things overview and application scenarios: 1) Adaptation to Environmental Knowledge, 2) Enhanced Music E-Learning, 3) Remote Rehearsals, Intelligent Mixing, and Interaction with the Cloud, 4) Smart Music Therapy, and 5) Augmented and Immersive Live Concert Experiences [2].

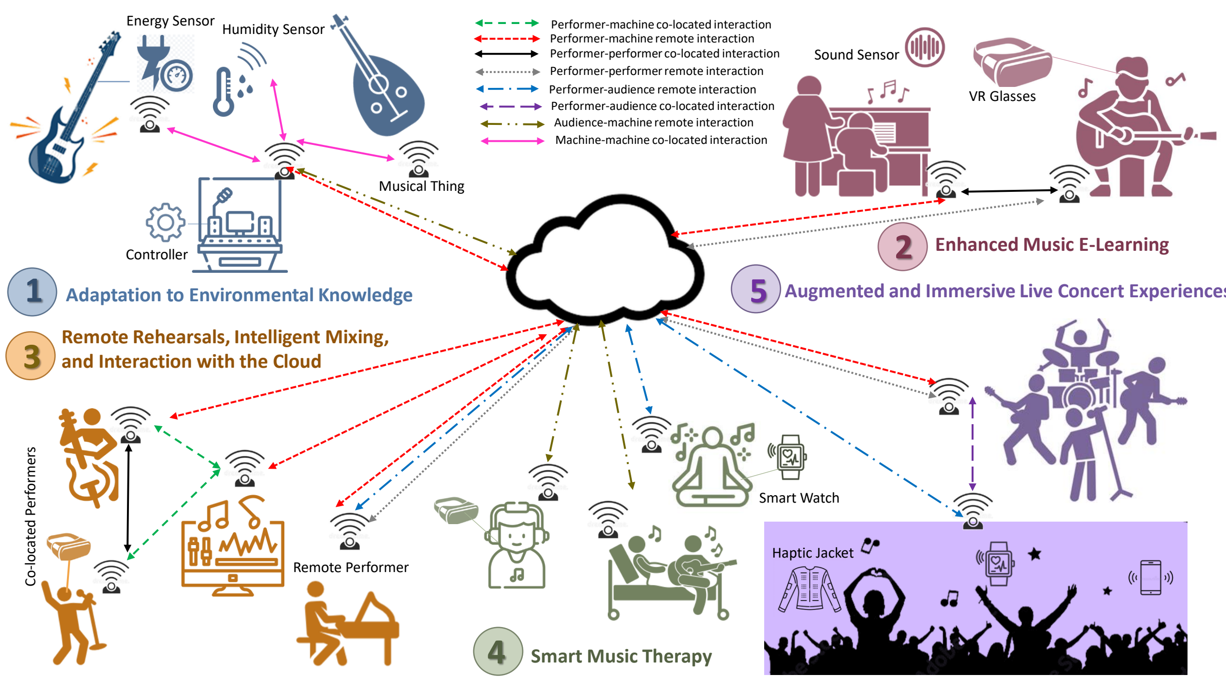

Fig. 3. Possible interactions between musicians, audience members, and machines in the Internet-of-Musical Things ecosystem.

guarantee resilience and scalability. Additionally, serverless computing paradigms will be needed to facilitate automation, where most of the development and deployment of distributed applications is performed on top of the network infrastructure. In this sense, regardless of the dynamic network changes, the application will always have access to a local computing service.

VI. A Spotlight on an Ecosystem: IoMusT

To put the discussion presented in this article into the context of an ecosystem and inspired by the highly sought-after new era of entertainment experiences [3], we illustrate the 6G driving UCs and technological perspectives for the recently envisioned futuristic IoMusT ecosystem [2] and the references therein. In this ecosystem, a new class of musical devices will

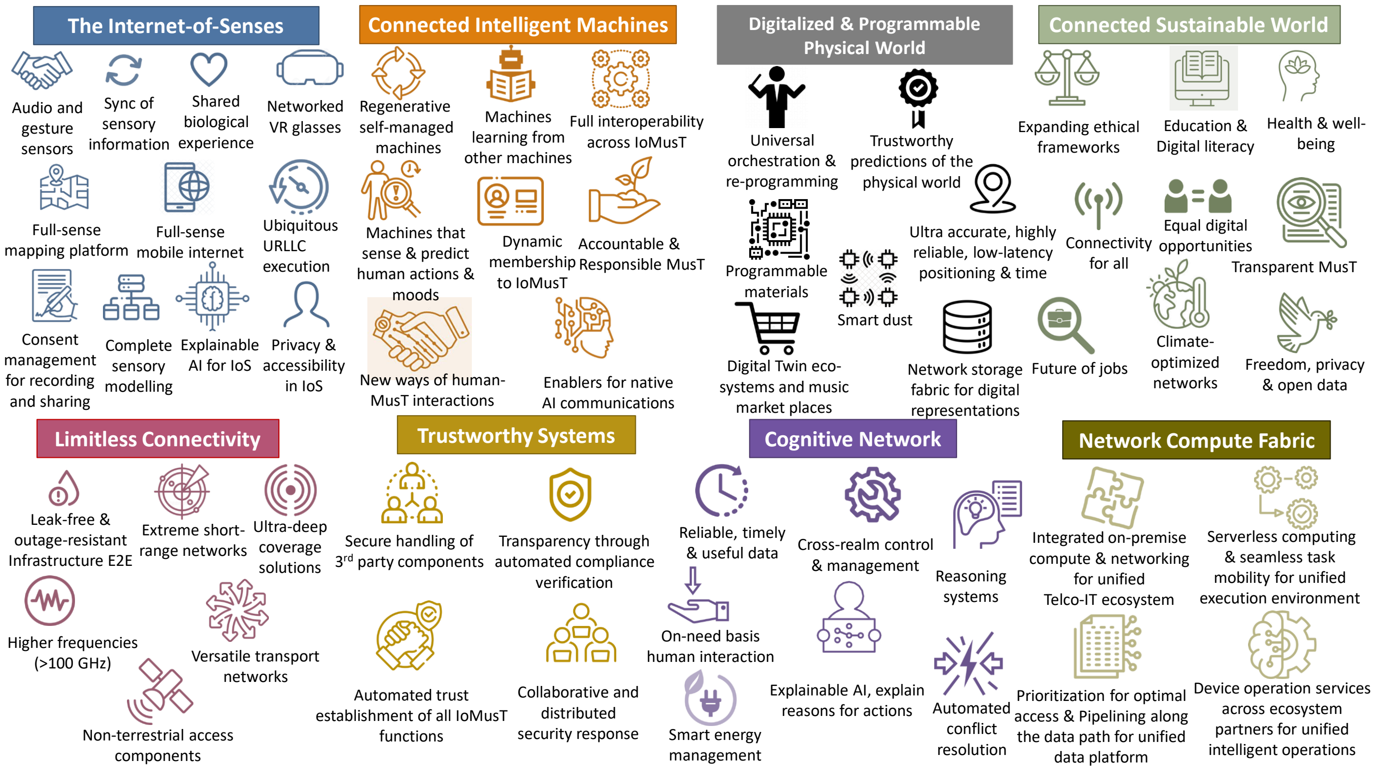

Fig. 4. The Internet-of-Musical Things journey through 6G driving use cases and technological perspectives.

be connected to the Internet, which could have a transformative effect on how humans involved in musical activities (e.g., performers, audiences) conduct these activities and interact with musical objects (e.g., musical instruments). IoMusT are a subclass of Things and therefore, inherit characteristics of Things, such as sensors, actuators, connectivity options, and software to collect, analyze, receive, and transmit data. Musical Things (MT) are entities that can be used in a musical context to produce musical content or to observe phenomena associated with musical experiences and can be connected to a local and/or remote network and act as sender and/or receiver and as such, interoperability and synchronization are key factors. An overview of IoMusT and the relevant potential application scenarios are presented in Fig. 2. Furthermore, the associated possible interactions in this ecosystem are depicted in Fig. 3.

The authors in [2] evaluated the latency and reliability of a 5G-enabled IoMusT when supporting Networked Music Performances (NMP) and quantified how the performance varies as a function of the number of IoMusT nodes and of different background traffic levels. In a study involving four musicians, findings showed that latency increased with the number of nodes and background traffic, while reliability metrics remained consistent. This suggests that packet loss and latency are caused by different network operations, not necessarily due to retransmissions at the radio link level. Based on real-time measurements, the average latency was below 24 ms for all conditions, whereas packet losses occurred on average with a probability of less than 10^2. Nonetheless, latency peaks and consecutive lost packets were observed, meaning that a continuous stream of reliable and low-latency communications cannot be maintained. This poses critical challenges for NMPs and suggests that current 5G designs are infeasible to support NMP support.

It is not difficult to comprehend from Figs. 2 and 3 and the evidence-based feasibility study in [2] that the deployment of IoMusT paradigm will depend on a significant level of scalability in control, compute, cognition, distribution, digitalization, and densification to foster novel and diversified services settings, transparency and affordance, collaboration and communication, access and privacy, and a range of interaction types ranging from real-time interactive to highly asynchronous [2]. Inspired by this, we illustrate in Fig. 4 several stepping stones, linking the IoMusT journey with the discussed 6G driving UCs and technological perspectives and the stepping stones outlined in Table II.

VII. Conclusion

With 5G deployment progressing in leaps and bounds, the focus has shifted towards NG communication networks. Although we are at a very early stage, where visions and predictions can be controversial, it is much anticipated that 6G will both build on the success points of previous generations and introduce revolutionary technologies and architectural shifts. This article presented a novel perspective on the 6G vision and the evolution of mobile networks towards this vision. To this end, we presented the 6G promise, portrayed through four driving UCs. To achieve the discussed promise, we introduced our vision of the six architectural pillars of 6G networks, and proceeded to highlighting key paradigms and corresponding technological advancements that will bring the anticipated 6G promise into reality.

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