Towards 6G - Hexa-X Project's Key Findings

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***Abstract*—We present key findings of the European 6G flagship project Hexa-X. An overview of the envisioned end-to-end architecture and key technical enablers is provided. We highlight the key performance and value indicators (KPIs and KVIs) for evaluating 6G systems. We present key findings based on the contributions made towards societal values in terms of KVIs, and performance evaluations in relation to the KPIs. Finally, we discuss the innovation potential of the enablers and the outlook of research and standardization towards 6G.**

***Index Terms*—6G, Hexa-X, Wireless communications, AI, ML, Sub-THz, Sensing, Network architecture, KPI, KVI.**

I. INTRODUCTION

As the fifth generation (5G) of mobile networks continue to be deployed, the research for the sixth generation (6G) is well underway. The International Telecommunication Union – Radio Sector (ITU-R), responsible for defining the requirements for mobile generations, prepared the recommendation for the IMT-2030 framework which serves as a roadmap for 6G research and development [1], [2]. Meanwhile, the European 6G Flagship project Hexa-X was launched in 2021 with the ambition to strongly contribute to harmonizing the global 6G vision and define the foundations for the end-to-end (E2E) 6G systems in cooperation with key stakeholders worldwide [3]. Hexa-X has contributed to the 6G structuring and framing as well as developing enablers and defining requirements for 6G with the vision to *connect human, physical, and digital worlds,* while also considering key societal values *sustainability*, *trustworthiness*, and *digital inclusion*. The 6G vision and relevant use cases have been discussed in several prior publications (see e.g. [3], [4], [5], [6]), and Hexa-X has contributed towards the 6G vision outlined in [3] and identified new widely accepted 6G use case families [7] (D1.4).

This paper shares insights from the Hexa-X project, detailing and assessing key candidate technologies for 6G, while acknowledging that it doesn't cover every potential technology. Section II outlines the proposed end-to-end 6G architecture and discusses different layers in the architecture, and the relevant enabling technologies in each layer. Section III presents key societal values to be considered for 6G and discusses the impact of these technologies on key value indicators (KVIs). The paper provides more detailed insights on these enabling technologies in Section IV and presents assessments in terms of the key performance indicators (KPIs). Section V concludes the paper by discussing the innovative capabilities of these technologies for 6G marketplace and outlines the future 6G research directions.

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II. E2E 6G ARCHITECTURE OVERVIEW

The envisioned E2E 6G architecture is presented in Figure 1, including network infrastructure, devices, cloud services and applications that work seamlessly together [7] (D1.4).

A. Architectural enablers towards 6G

There are several technical enablers that make the 6G architecture a step forward in comparison with the previous generation. Massive usage of *AI*, e.g., for potential AI-driven air interface and AI-as-a-Service (AIaaS), *flexibility* which is achievable by programmability feature of the network and flexible resource allocation techniques, *cloudification*, *softwarisation* and *continuum orchestration* are the few novel components that 6G architecture should be able to support.

Security and privacy need to be inherent part of 6G. To lay the foundations for this, relevant security and privacy technologies including *physical layer security*, *AI/ML security*, *distributed ledger*, *quantum security*, are identified and mapped to the E2E 6G architecture, resulting in an E2E security architecture [7] (D1.4).

B. Layers in the E2E architecture

To handle the 6G use cases, the proposed 6G architecture is inherently built on an *infrastructure and cloud layer*. The *network service layer* supports the exposure of existing and new services to the *application layer*. *Artificial intelligence (AI) and analytics* are pervasive functions cutting across all layers of the 6G architecture, while *management and orchestration* (M&O) provides control to all layers.

The ***infrastructure and cloud layer*** of the E2E 6G architecture encompasses physical resources required for the high level of quality of service (QoS) experience promised by 6G. This forms the backbone of the 6G network and provides physical resources to host the network communication services and beyond communication services, such as sensing and localization, as well as cloud applications and application layer elements. Key enablers include (i) *radio access technologies* along with the related advancement in design, hardware and channel modelling, and signal processing; (ii) *AI-driven air interface* that leverage on AI using machine learning (ML) capabilities to learn signal processing functionalities from data to improve network performance [8];

(iii) *Network of networks*, where sub-networks coordinate among each other in a unified system to provide global coverage in remote and underserved areas, where non-

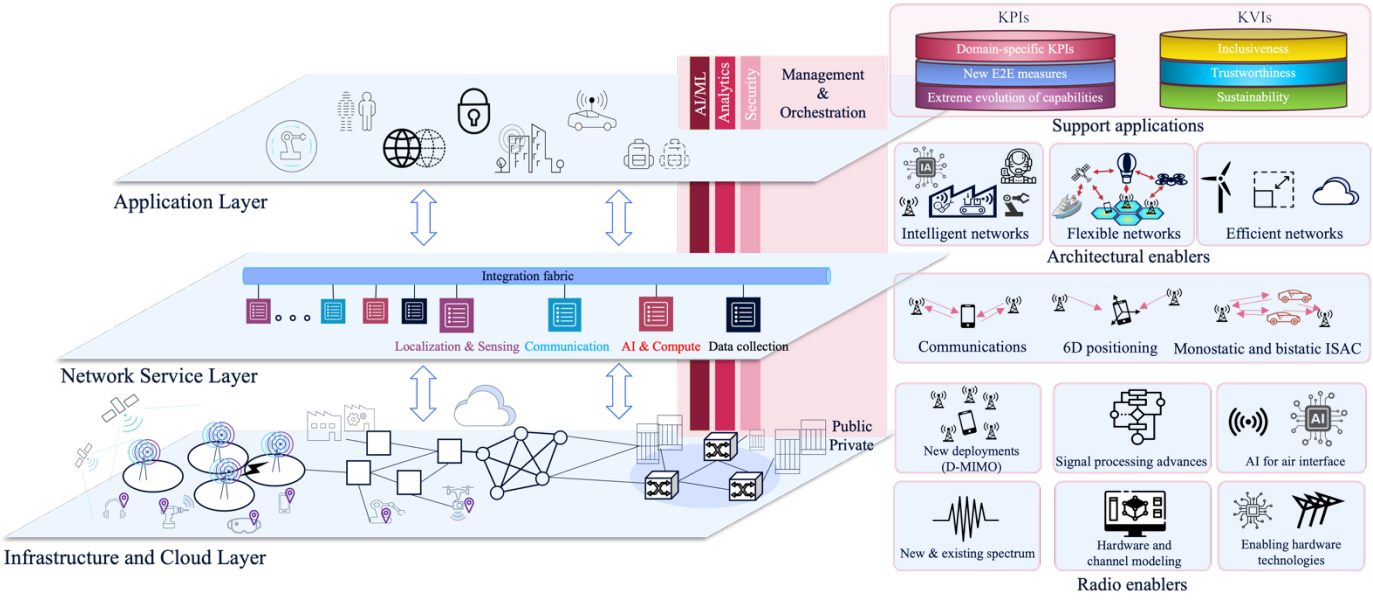


Figure 1. 6G E2E architecture comprising the infrastructure and cloud layer providing the physical resources, the network service layer providing services to end-users, and the application layer interacting directly with end-users. The radio enablers associated to the infrastructure and cloud layer and the architectural enablers associated to the network service layer are illustrated beside the respective layers. The considered KPIs and KVIs are mentioned.

terrestrial network (NTN) will play an important role. The ***network service layer*** is responsible for providing various services to end-users. It also depicts *network functions (NFs)* spanning from central clouds to the extreme edge cloud for a range of services including communication, localization and sensing, data collection, and AI and compute as depicted in Figure 1. The E2E 6G architecture is envisioned to integrate *extreme edge*, which is part of a network with high heterogeneity of devices, characterized by a wide variety of technologies, in terms of both hardware and software. The integration of the extreme edge as part of the E2E network can enable new use cases that rely on the vast and heterogeneous infrastructure pool of resources.

The ***application layer*** directly interacts with end-user applications, facilitates the exchange of data and information, and supports a wide range of use cases including but not limited to the identified use case families in Hexa-X.

C. Management and Orchestration

M&O controls all elements of the E2E 6G architecture. Built on top of the former 5G architectural view from the 5G-PPP Architecture Working Group [9], M&O introduces novel capabilities to address challenges posed by the 6G technologies [7] (D6.2). These capabilities include unified orchestration across the extreme-edge, edge, and core continuum; unified M&O across multiple domains that could be owned and administered by different stakeholders; an increased level of automation leveraging on closed-loop and zero-touch solutions; the adoption of data-driven and AI/ML techniques in the M&O system; the possibility of introducing intent-based approaches for service planning and definition and the adoption of the cloud-native principles considering, not only the usage of micro-services and exposed interfaces, but also enabling mechanisms for the network services to be deployed and updated.

III. Key-Value Contributions of the Technical Enablers

Hexa-X broadens network design beyond performance. Hexa-X adopted a value-oriented approach via Key Values (KVs) important to humans and society: sustainability, trustworthiness, and inclusiveness. This requires establishing new evaluation metrics, denoted as KVIs, and integrating them into the 6G design and development illustrated in Figure 1 [10], [11]. Hexa-X utilizes the term KVI to distinguish it from KPI, still used for instance by ITU-T [12]. The following sections provide an overview of KVs and corresponding KVIs, and discusses the contributions of Hexa-X 6G enablers to these values.

A. Sustainability

Environmental sustainability aims to protect natural resources and ecosystems through efficient resource use, waste reduction, and promoting recycling and sustainability practices. *Economic sustainability* seeks to ensure continuous economic growth, balancing the needs of organizations with those of society. *Social sustainability* focuses on enhancing quality of life, and community welfare, ensuring everyone has access to basic necessities.

Hexa-X emphasizes sustainability in 6G, with 6G itself needing to be sustainable as well as recognizing opportunities for making other fields more sustainable with 6G, aiding in the achievement of UN sustainable development goals (SDGs). Among the recognized sustainable innovations, sensing

capabilities can help weather monitoring and cost-effective solutions for reducing pollution. Ambient backscatter communication brings zero-energy asset tracking. Co-optimized semiconductor technology-aware modelling optimizes use of scarce resources. Efficient resource allocation techniques improve resource usage.

Flexible radio design and D-MIMO transmission schemes allow optimizing the deployment to meet specific performance requirements while minimizing power usage and footprint. Energy-efficient transmission solutions have been developed, such as hardware-aware waveform design, and proactive location-based resource allocation. At the receiver side, low-complexity AI/ML-based processing has been used for channel estimation and mitigating signal detection under hardware impairments, leading to energy efficiency. Furthermore, the developed Communication-Computation-Control-Codesign (CoCoCoCo) approach, and goal-oriented communications, enhance communication efficiency.

B. Inclusiveness

Inclusiveness denotes broad ability and ease for individuals and groups to access and utilize services, aiming to bridge digital divides. Technically, inclusiveness encompasses network and service availability across various spatial and temporal settings. It prioritizes services availability and accessibility to diverse groups, including the elderly, children, and those marginalized because of location, gender, culture, health or education.

Hexa-X contributes to inclusiveness through several technical innovations. Flexible radio design adapts transmission across various frequency bands and devices, making services accessible to users with diverse economic backgrounds. D-MIMO transmissions improve network coverage and scalability. Integrating localization and sensing into cellular networks enables gesture recognition, aiding disabled individuals. This integration facilitates monitoring persons at an affordable cost, including monitoring the elderly, chronic patients, and infants. Mesh ad hoc networks provide on-demand coverage, while the integration of NTN architecture with 6G expands global service coverage to remote areas. Novel Human-Machine Interfaces (HMIs) and the integration of digital twins (DTs) offer new opportunities for remote education, work, and assistance.

C. Trustworthiness

Trustworthiness is an essential key value in 6G, including to safeguard data and resilience to address both deliberate and accidental issues like environmental disturbances and errors. It also covers reliability and integrity, ensuring secure and ethical interactions across devices and networks. Privacy is focused on preventing unauthorized disclosure of information.

Hexa-X presents various enablers to enhance trustworthiness. Developed channel and hardware models facilitate design of reliable communication systems. D-MIMO transmission schemes are tailored to improve reliability. By spreading out antennas over a larger area, an eavesdropper would need to be close to multiple antennas simultaneously to intercept the complete signal. The integrating of localization and sensing into communication systems acts as a supportive mechanism to minimize potential harm to the environment, equipment, or humans. Federated learning contributes to privacy by keeping data on local devices or servers, while AI provides new strategies against threats. Data exposure frameworks are developed to manage trust for in-network learning. The CoCoCoCo framework and dependability enablers facilitate the realization of Industrial 4.0, and a trustworthy DT platform ensures privacy-preserving collaboration among DTs.

IV. 6G TECHNICAL ENABLERS AND PERFORMANCE EVALUATIONS

Hexa-X has several enablers to be integrated into the E2E 6G architecture including radio access technologies for extreme communication performance and high-resolution localization and sensing, connecting intelligence, and network evolution and expansion towards intelligent, flexible, and efficient networks. In addition to the contributions of these enablers towards different KVIs as discussed in Section III, to evaluate system performance and set the requirements on 6G system design, Hexa-X identified the need for *three types* of KPIs: (i) *conventional KPIs* to be enhanced for 6G (e.g., data rates, spectral efficiency, reliability, capacity, coverage, and latency), (ii) novel *E2E KPIs* measuring E2E system performance (e.g., dependability of services), and (iii) new *domain-specific KPIs* capturing novel capabilities within 6G systems (e.g., localization and sensing, AI, and compute capabilities), as shown in Figure 1 and further discussed in [3]. In the following sections, an overview of enablers for these objectives are presented. The achieved performance for use cases with respect to the mentioned KPIs are provided.

A. Radio access enabling technologies

The considered technological components for 6G radio are illustrated in Figure 1 and are outlined in the following.

Spectrum*:* Thanks to the decisions at WRC-23 [13], 6G will start via using quite similar frequencies as today, offering an economical approach. Due to the need to address the continuous and strong growth in wireless traffic and to understand the realities offered by higher frequencies, Hexa-X studied other frequencies as well.

Channel model*:* Hexa-X developed channel models at 140 GHz based on measured spatio-temporal channel sounding data in indoor and outdoor scenarios serving as basis for future sub-THz channel models. The project also developed models for material and wave interactions based on measurements of material permittivity and conductivity measurements for a variety of materials in the frequency range of 2 to 260 GHz. The models served as the basis for design and evaluation of the physical layer methods for both communication and sensing. However, the studies on integrated sensing and communication (ISAC) revealed that existing stochastic models may not be suitable for assessing sensing performance, due to their inability to support passive objects in a spatially and temporally consistent fashion.

Hardware model*:* Non-ideal behavior of RF hardware limits system performance. This is even more challenging at higher frequencies and wider bandwidths. Therefore, models were developed for hardware impairments for the design and assessment of physical layer methods for communication and sensing. Parametric phase noise models were developed for

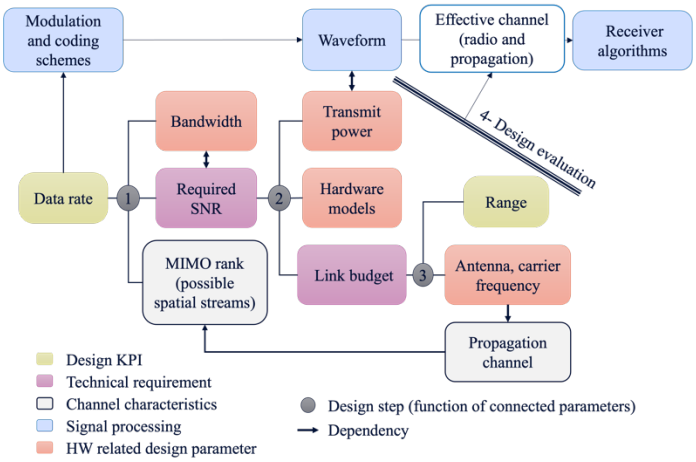


Figure 2 Radio design methodology for specifying radio design parameters to fulfil system requirements.

mm-wave and sub-THz and compared with the existing upscaled 3GPP reference models.

Waveforms: Hexa-X outlined guidelines for waveform design and investigated exemplary waveforms including DFT-spread OFDM. It is recommended to decrease frame processing time with an order of magnitude to fulfill the strict latency requirements; to choose waveform with small envelope variation to cope with PA nonlinearity; to select a resilient waveform to phase noise; to incorporate receiver methods for compensating PA non-linearity and phase noise; and to design waveforms that enable use of analog to digital converters (ADCs) with smaller sampling rate or smaller resolution for operation at extreme bandwidths.

D-MIMO: Hexa-X explored D-MIMO architectures for fronthaul, transmission, processing, and deployment and evaluated analogue and digital approaches to manage increased processing demands. It introduced solutions such as radio stripes for cost and energy efficiency, coordinated transmission for mobility, network-controlled repeaters for overcoming blockage, and Integrated Access and Backhaul (IAB) to enhance network flexibility and scalability. Hexa-X highlights ability of D-MIMO to improve coverage, reduce energy consumption, and increase capacity and reliability through joint transmissions. The spatial dimension provided by large or distributed arrays provides improved resolution for sensing. Accurate sensing information can be used for directing beams.

Radio design methodology: Hexa-X developed a systematic frequency agnostic radio design methodology outlined in Figure 2 to specify the design parameters such as antenna array size, maximum PA output power, resolution of analog-to-digital (ADC) converters. For instance, to achieve a targeted peak data rate, the required SNR is calculated with respect to the bandwidth and available spatial beams. The link budget necessary to meet SNR at a given range is determined by considering antenna parameters and transmit power, as well as the impacts of hardware, waveform, and the propagation channel. This procedure can be followed to achieve certain angular and range resolution for sensing. It is shown that sub-array-based RF transceiver is a practically feasible architecture for above100 GHz to overcome HW design complexity while

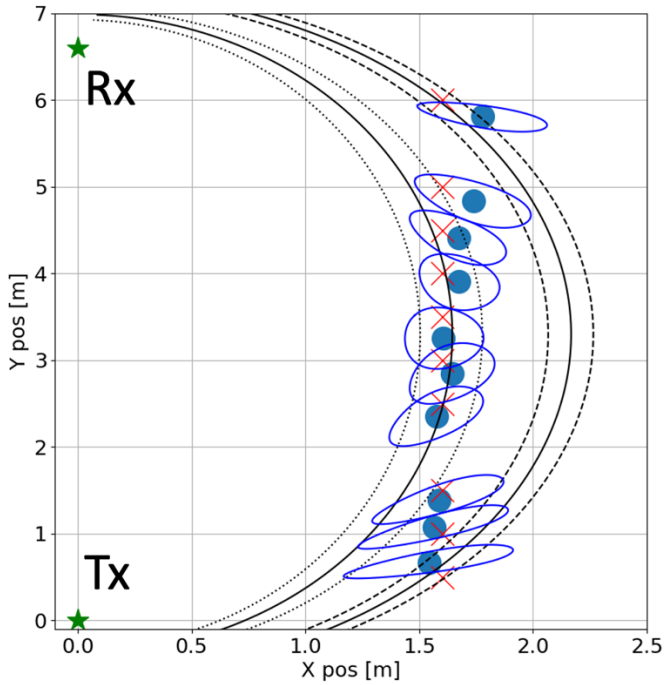


Figure 3. Bistatic ISAC for passive object detection with OFDM waveforms. The green stars represent the transmitter and receiver location. The red crosses show the ground-truth, the blue dots the estimates from angle measurements (included error ellipses), and the lines represent the distance measurements and their uncertainties.

providing efficient beamforming and spatial multiplexing capabilities.

Integrated communication and sensing: While higher frequency bands are most attractive for extreme sensing performance, thanks to large available bandwidths and antenna arrays, lower bands have significant sensing potential, especially under phase-coherent operation among distributed nodes (e.g., in D-MIMO) or among different frequency bands. Hexa-X has proposed several technical enablers for ISAC to provide high-resolution localization and sensing including novel methods for joint 3D position and orientation estimation, optimized signals in space, time, and frequency domains to optimize communication and sensing trade-offs, AI-driven solutions to monostatic and bistatic ISAC, as well as technologies for improving communication metrics by harnessing location and sensing information as illustrated in Figure 1. Dynamic blockage avoidance technique levering on the sensing capability has been shown to achieve a throughput gain of 33%. Additionally, utilization of a channel knowledge map can reduce overhead, e.g., in terms of reducing the required pilot signals to be transmitted and result in gains in spectral efficiency (exceeding 100%) and energy efficiency (exceeding 200%) compared to conventional beam training at sub-THz frequencies.

Figure 3 shows a practical realization of ISAC using 60 GHz radios for bistatic sensing with 5G NR OFDM waveforms with extended subcarrier spacing (960 kHz). Background subtraction was followed by an angle (from beam power measurements) and delay estimation (from FFT processing), resulting that a person could be positioned with sub-meter accuracy.

1. Key performance achievements of radio access enablers

The presented radio access enablers, illustrated in Figure 1, can achieve performance for communication and sensing as discussed in the following [7] (D2.3, D3.3):

Throughput: To achieve throughputs exceeding 100 Gbps in the sub-THz frequency range, channel and RF hardware models were developed, and radio access schemes designed [7] (D2.3). 100 Gbps seem to be within the reach even above 100 m link distances with a reasonable number of antennas (~1000). However, the bandwidth required is a major challenge for RF hardware but even more for conversion to digital domain and digital signal processing. Reasonable power consumption per bit would require parallelism and new architectures. Additionally, research has been conducted on hardware-aware waveform and modulation schemes that demonstrate robustness against common hardware impairments such as power amplifier (PA) nonlinearity, phase noise, and analog-to-digital converter (ADC) resolution limitations.

Latency: Hexa-X has evaluated the feasibility of achieving sub-0.1 ms latency in radio access at sub-THz transmission. This is accomplished by leveraging ultrawide-bandwidth transmission for short transmission intervals, utilizing low-complexity waveforms such as OFDM-variants to reduce the processing time, employing high-reliability detection schemes to reduce the number of retransmissions, and implementing location-assisted beam tracking techniques to reduce beam tracking time. For example, considering 5G New Radio (NR) standard numerologies with FFT size 4096, user plane latency of 0.1 ms is achievable at numerologies larger than μ=5 (subcarrier spacing of 480 kHz and bandwidth of 2 GHz), using a transmission slot size of 1 or 2 OFDM symbols, and processing time of the order of 1-2 slots and one re-transmission. These strategies can enable the realization of ultra-low latency communication in the sub-THz frequency range.

Spectral efficiency: By deploying many antennas in a distributed manner and integrating access and backhaul functionalities, the system can achieve higher spectral efficiency by maximizing the utilization of available resources and enabling efficient multiplexing of multiple data streams. In comparison with centralized massive MIMO, D-MIMO allows flexible deployment, enhanced coverage, mitigating blockage and fading, better load balancing, improved interference management, and reduced pilot contamination.

Reliability: To provide diversity gains and enhance reliability, D-MIMO with multi-connectivity and coherent joint transmission techniques have been proposed. By utilizing multiple antennas distributed across the system, multi-connectivity allows for simultaneous communication over multiple paths. Coherent joint transmission ensures synchronized transmission across these paths, resulting in improved reliability by mitigating the fading and interference. The combination of D-MIMO, multi-connectivity, and coherent joint transmission techniques enhances the overall system reliability and robustness. Multi-connectivity and D-MIMO are beneficial from a sensing perspective as well, as sensing typically relies on direct links to and from targets or users, which is more probable under multi-connectivity operation.

Sensing and positioning accuracy: By virtue of large bandwidths and array apertures (with respect to the wavelength) at higher carrier frequencies, fusion of time, Doppler, and angle measurements lead to an object localization error of less than 1 m for 90% of cases. When models are not available, AI-based human activity detection has achieved an accuracy of 70%-90%, while an AI-based landscape detection can achieve an accuracy of up to 90%. In terms of positioning connected devices at sub-THz, by fusing time and angle measurements, the 3D position and 3D orientation of a user device can be estimated from a single base station (BS) with high accuracy (cm-level and degree-level), having at least one strong signal reflection. At lower bands, multipath resolvability becomes a limitation to the accuracy, providing opportunities for AI-based approaches.

B. Enablers towards connecting intelligence

In the context of Hexa-X, four solution categories were identified and studied [7] (D4.3). First, *Network performance enhancement using AI/ML in 6G*. The focus was on radio access network performance improvements over classical design methods. AI-driven air interface design, illustrated in Figure 1, was proposed for methods including channel estimation, waveform learning, PA post distortion compensation and beam selection for D-MIMO. Improvements in E2E network M&O were studied, such as AI-based predictive orchestration and distributed AI for automated user plane function (UPF) scaling in low-latency network slices. Second, *6G network as an efficient AI platform*, focuses on seamless and pervasive in-network AI operation including the enabling of UEs to exploit network knowledge through the AIaaS concept. This was complemented by scalable solutions for distributed AI applications such as load balancing in federated learning, enhancing computation and communication efficiency. Third, *AI/ML as an enabler for 6G network sustainability* comprised strategies to use AI to enhance network sustainability. To reduce complexity, frugal AI introduces methods for which the training phase is designed to be sustainable and AI-based semantic communication leads to a new perspective, viewing communications beyond reconstructing the exact symbols of the source at the destination. Fourth, *privacy, security & trust in AI-enabled 6G* becomes critical for AI-pervasive 6G because AI-based decisions are done for autonomy of communication and detection of cyber-attacks. Finally, *AI/ML for orchestration and management*, i.e., the regular fulfillment, assurance, and artifact management functions, can be enriched by AI [7] (D6.3).

***AI regulations**:* Hexa-X has been closely following activities related to the preparation of the EU Artificial Intelligence Act (EU AI Act) through a close relationship with ETSI [14].

1. Key performance achievements of connecting intelligence enablers

The four solution categories of the outlined connecting intelligence lead to performance gains, examples of which are detailed below [7] (D4.3):

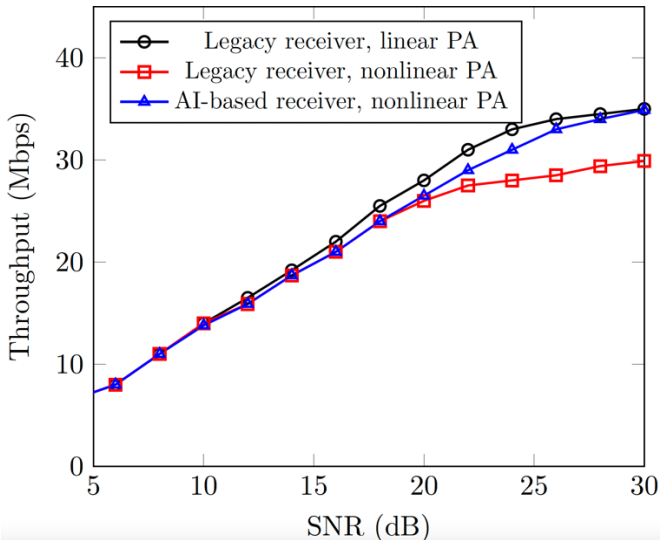


Figure 4 Performance of the AI-based receiver compared to the legacy receiver for PA post distortion compensation of DFT-s-OFDM signals.

Improved throughput and reliability: Dealing with RF hardware impairments is challenging for transmissions at higher frequency bands and for higher energy efficiency. Here AI techniques assist with signal detection and enhance reliability and throughput. For example, an AI-based receiver for PA post distortion compensation can achieve 20% throughput gain compared to legacy receiver as shown in Figure 4, and improve reliability by achieving approximately 1 dB signal to noise ratio (SNR) gain at a Block Error Rate (BLER) of 10%. This receiver uses a neural network demapper optimized for soft bit computation in the presence of distortions caused by PA non-linearity. Moreover, the proposed receiver can reduce the need for in-band distortion linearization techniques at the transmitter side, enhancing the energy efficiency of transmitters. This is particularly beneficial in uplink communication in cellular networks, where user equipment faces constraints in processing capability and energy budget, and in downlink scenarios to boost throughput and base station coverage, further improving the energy efficiency of base stations.

Reduced latency: Beamforming is essential to provide reliable coverage in higher frequency bands, where narrow beams increase beamforming gains, capacity, and coverage but also complicate beam selection due to higher overhead and strict latency requirements. The issue intensifies in D-MIMO environments with numerous Access Points (APs), each equipped with multiple antennas and beam directions. By leveraging AI-assisted low complexity beam selection, the latency of beam selection can be reduced by a factor of more than 50 times compared to the sequential beam sweeping approach. To address this, compressed sensing (CS)-based beam identification is proposed to reduce the best beam selection delay. This method requires fewer measurements than the number of beams by exploiting channel sparsity in the angular domain. The approach is particularly advantageous in high mobility situations where rapid beam changes are essential to maintain low-latency connections.

C. Architectural enablers towards intelligent, flexible, and efficient networks

The evolution of the networks demands more intelligent, flexible and efficient networks to handle the new use cases described in [3], see Figure 1. To enable *intelligent networks*, an architecture AIaaS framework for both in-network AI and exposed AIaaS have been developed [7] (D5.3). The framework consists of a set of common services and functions as well as a unified exposure through a common application programming interface (API) framework. *Flexible networks* aim to enable extreme performance, scalability, and global service coverage that can be extended from core, edge and far edge. A new framework for mesh ad hoc device networks to enable an increased coverage and capacity on a demand basis is developed [7] (D5.3). Global service coverage is shown feasible assuming a realistic satellite network constellation allowing efficient inter-satellite-link hops. The 6G architecture should be *efficient*, both in terms of signalling, scalability and energy efficiency. In [7] (D5.3), a concept with fewer interfaces and processing points were developed, leading to decreased signalling latency.

1. Key performance achievements of the architectural enablers

The achieved performance enablers for intelligent, flexible, and efficient networks are summarized below.

Improved network reliability: The integration of NTN with TN (Terrestrial Networks) can enable a 99% global service coverage [7] (D5.3). Proposals for mesh ad-hoc networks on demand and 6G multi-connectivity solutions further enhance network reliability [7] (D5.3). The CoCoCoCo framework, designed to model and utilize the impact of packet losses on control applications, achieves an impressive reliability improvement of seven orders of magnitude of the mean time-to-failure [7] (D7.2) with only an 18% increase in resource utilization. Distributed massive MIMO and unmanned aerial vehicle (UAV) assisted mMTC techniques are also employed to enhance network reliability. Trajectory optimizations are utilized to minimize cross-channel interference [7] (D7.2).

Improved signalling: Through improved core network and RAN function design and placement, the handover procedure signalling reduction of 20% has been demonstrated [7] (D5.3). One factor for the decrease in signalling time is that the new design avoids the high layer split in RAN. Some NFs in the core network are also combined to further decrease the procedure signalling time.

Energy efficiency: Intelligent networks leverage federated learning models, resulting in 8% energy saving. Utilization of ambient backscatter communications for zero-energy tracking shows potential for achieving energy autonomy [7] (D7.2).

E2E Latency: In UAV-assisted mMTC scenarios, a notable 30% reduction in the age of information has been achieved, enhancing the timeliness of transmission. Deterministic control and data plane latency are achieved during network reconfigurations, minimizing latency [7] (D5.3).

V. Innovation Potential, Conclusions, and Outlook

The assessment of innovations in Hexa-X in terms of possible market exploitation revealed preliminary considerations for

adoption of 6G technologies [15]: (i) the innovations foresee need for mobile network operators (MNOs) to expand their collaborations with other sectors (e.g., verticals); (ii) the innovations will enable innovative 6G services, where the main market beneficiaries are MNOs and equipment manufacturers (OEMs); (iii) the majority of innovations help expanding stakeholders' market share, while only for a minority is clear how to enable total addressable market (TAM) expansion. A key aspect for their deployment in future 6G systems will be a joint success of technical implementation and benefits for targeted users, but also proper business decisions from stakeholders (e.g., MNO and verticals) in terms of possible 6G market expansions.

This paper presented an overview of the envisioned 6G E2E architecture, key technological enablers and their assessments with respect to KPIs and KVIs. These have built a solid base to continue towards the next steps of 6G with an increasing role of pre-standardization, initial E2E system view and validation. During 2025, the momentum in 6G could move from leading research consortia to standardization. The follow-up project Hexa-X-II expands from research to systemization analysis, early validation, and proof of concept. It progresses from the 6G key enablers to advanced technology readiness including key aspects of modules, protocols and interfaces, and data. Hexa-X-II designs a system blueprint aiming at the sustainable, inclusive, and trustworthy 6G platform that should meet the future needs of serving and transforming society and business.

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