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Effect of 6G Network in our Environment

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Abstract: *The ongoing deployment of 5G cellular systems is continuously exposing the inherent limitations of this system, compared to its original premise as an enabler for Internet of Everything applications. These 5G drawbacks are spurring worldwide activities focused on defining the next-generation 6G wireless system that can truly integrate far-reaching applications ranging from autonomous systems to extended reality. Despite recent 6G initiatives[1], the fundamental architectural and performance components of 6G remain largely undefined. In this paper, we present a holistic, forward-looking vision that defines the tenets of a 6G system. We opine that 6G will not be a mere exploration of more spectrum at high-frequency bands, but it will rather be a convergence of upcoming technological trends driven by exciting, underlying services. In this regard, we first identify the primary drivers of 6G systems, in terms of applications and accompanying technological trends. Then, we propose a new set of service classes and expose their target 6G performance requirements. We then identify the enabling technologies for the introduced 6Gservices and outline a comprehensive research agenda that leverages those technologies. We conclude by providing concrete recommendations for the roadmap toward 6G. Ultimately, the intent of this article is to serve as a basis for stimulating more out-of-the-box research around 6G.*

Keywords: 6G

I. INTRODUCTION

Each generation of mobile technology, from the first to the fifth (5G), has been designed to meet the needs of end users and network operators, as shown in Fig. However, nowadays societies are becoming more and more data-centric, data dependent and automated. Radical automation of industrial manufacturing processes will drive productivity. Autonomous systems are hitting our roads, oceans and air space. Millions of sensors will be embedded into cities, homes and production environments, and new systems operated by artificial intelligence residing in local 'cloud' and 'fog' environments will enable a plethora of new applications.

Communication networks will provide the nervous system of these new smart system paradigms. The demands, however, will be daunting. Networks will need to transfer much greater amounts of data, at much higher speeds. Furthering a trend already started in 4G and 5G, sixth generation (6G) connections will move beyond personalized communication towards the full realization of the Internet of Things (IoT) paradigm, connecting not just people, but also computing resources, vehicles, devices, wearables, sensors and even robotic agents. 5G made a significant step towards developing a low latency tactile access network, by providing new additional wireless nerve tracts through (i) new frequency bands (e.g., the millimeter wave (mmWave) spectrum), (ii) advanced spectrum usage and management, in licensed and unlicensed bands, and (iii) a complete redesign of the core network. Yet, the rapid development of data-centric and automated processes, which require a datarate in the order of terabits per second, a latency of hundreds of microseconds, and 10^7 connections per km^2, may exceed even the capabilities of the emerging 5G systems.

To date, the wireless network evolution was primarily driven by a need for higher rates, which mandated a continuous 1000x increase in network capacity. While this demand for wireless capacity will continue to grow, the emergence of the Internet of Everything (IoE) system, connecting millions of people and billions of machines, is yielding a radical paradigm shift from the rate-centric enhanced mobile broadband (eMBB) services of yesteryears towards ultra-reliable, low latency communications (URLLC).

Although the fifth generation (5G) cellular system was marketed as the key IoE enabler, through concerted 5G standardization efforts that led to the first 5G new radio (5G NR) milestone and subsequent 3GPP releases, the initial premise of 5G – as a true carrier of IoE services – is yet to be realized. One can argue that the evolutionary part of 5G (i.e., supporting rate-hungry eMBB services) has gained significant momentum, however, the promised revolutionary outlook of 5G – a system operating almost exclusively at high- frequency millimeter wave (mmWave) frequencies and enabling heterogeneous IoE services – has thus far remained a mirage. Although the 5G systems that are currently being marketed will readily support basic IoE and URLLC services (e.g., factory automation), it is debatable whether they can deliver tomorrow's smart city IoE applications. Moreover, although 5G will eventually support fixed-access at mmWave frequencies, it is more likely that early 5G roll-outs will still use sub-6 GHz for supporting mobility.
Meanwhile, an unprecedented proliferation of new IoE services is ongoing.
Examples range from extended reality (XR) services (encompassing augmented, mixed, and virtual reality (AR/MR/VR)) to telemedicine, haptics, flying vehicles, brain-computer interfaces, and connected autonomous systems. These applications will disrupt the original 5G goal of supporting short-packet, sensing-based URLLC services. To successfully operate IoE services such as XR and connected autonomous systems, a wireless system must simultaneously deliver high reliability, low latency, and high data rates, for heterogeneous devices, across uplink and downlink. Emerging IoE services will also require an end-to-end co-design of communication, control, and computing functionalities, which to date has been largely overlooked. To cater for this new breed of services, unique challenges must be addressed ranging from characterizing the fundamental rate-reliability-latency tradeoffs governing their performance to exploiting frequencies beyond sub-6 GHz and transforming wireless systems into a self-sustaining, intelligent network fabric which flexibly provisions and orchestrates communication-computing control-localization-sensing resources tailored to the requisite IoE scenario.
Every new cellular generation is driven by innovative applications. 6G is no exception: It will be borne out of an unparalleled emergence of exciting new applications and technological trends that will shape its performance targets while radically redefining standard 5G services. Next, we first introduce the main applications that motivate 6G deployment and, then, discuss ensuing technological trends, target performance metrics, and new service requirements.

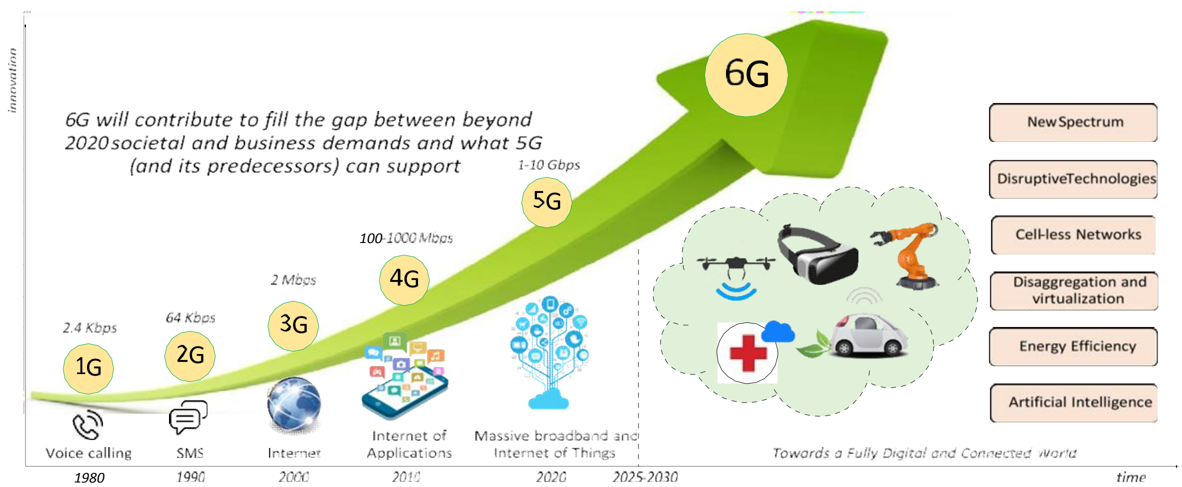

Fig: Novel disruptive communication technologies:

although 5G networks have already been designed to operate at extremely high frequencies, e.g., in the mm Wave bands in NR, 6G could very much benefit from even higher spectrum technologies, e.g., through Terahertz and optical communications.

Innovative network architectures:

Despite 5G advancements towards more efficient network setups, the heterogeneity of future network applications and the need for 3D coverage calls for new cell-less architectural paradigms, based on the tight integration of different

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communication technologies, for both access and backhaul, and on the disaggregation and virtualization of the networking equipment.

Integrating Intelligence in the Network:

We expect 6G to bring intelligence from centralized computing facilities to end terminals, thereby providing concrete implementation to distributed learning models that have been studied from a theoretical point of view in a 5G context. Unsupervised learning and knowledge sharing will promote real-time network decisions through prediction.

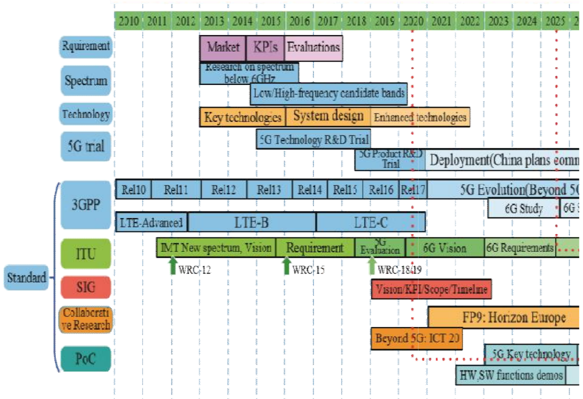

Fig: Roadmap of 6G

II. 6G USE CASES

5G presents trade-offs on latency, energy, costs, hardware complexity, throughput, and end-to-end reliability. For example, the requirements of mobile broadband and ultra-reliable, low-latency communications are addressed by different configurations of 5G networks. 6G, on the contrary, will be developed to jointly meet stringent network demands (e.g., ultra-high reliability, capacity, efficiency, and low latency) in a holistic fashion, in view of the foreseen economic, social, technological, and environmental context of the 2030 era.

In this section, we review the characteristics and foreseen requirements of use cases that, for their generality and complementarity, are believed to well represent future 6G services. Fig. provides a comprehensive view on the scenarios in terms of different Key Performance Indicators (KPIs). Augmented Reality (AR) and Virtual Reality (VR): 4G systems unlocked the potential of video-over-wireless, one of the most data-hungry applications at the time. The increasing use of streaming and multimedia services currently justifies the adoption of new spectrum (i.e., mmWaves) to guarantee higher capacity in 5G. However, this multi-Gbps opportunity is attracting new applications which are more dataheavy than bi-dimensional multimedia content: 5G will trigger the early adoption of AR/VR. Then, just like video-overwireless saturated 4G networks, the proliferation of AR/VR applications will deplete the 5G spectrum, and require a system capacity above 1 Tbps, as opposed to the 20 Gbps target defined for 5G. Additionally, to meet the latency requirements that enable real- time user interaction in the immersive environment, AR/VR cannot be compressed (coding and decoding is a time-consuming process), thus the per- user data rate needs to touch the Gbps, in contrast to the more relaxed 100 Mbps 5G target

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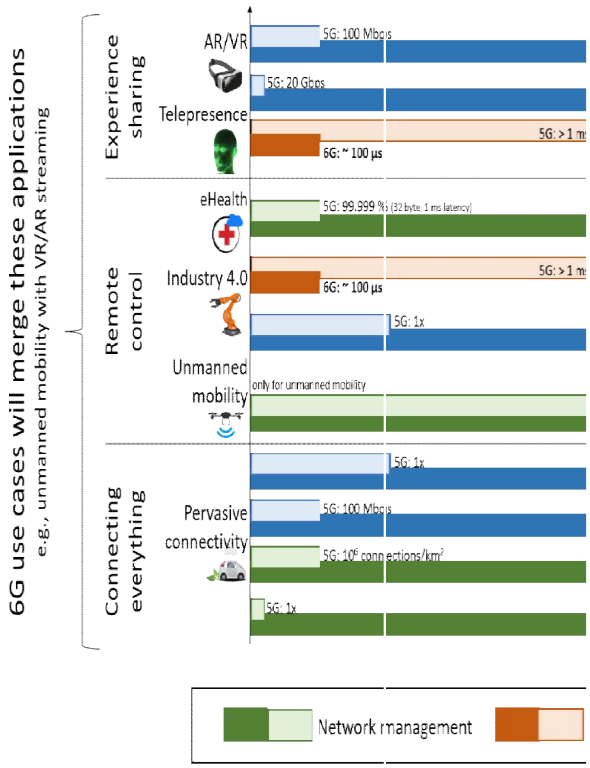

Fig : Representation of multiple KPIs of 6G use cases, together with the improvements with respect to 5G networks, using data from [1]–[9].

III. 6G ENABLING TECHNOLOGIES

Challenges of each proposed technological innovation and suggests which of the use cases introduced in Sec. II they empower. Although some of these innovations have already been discussed in the context of 5G, they were deliberately left out of early 5G standards developments (i.e., 3GPP NR Releases 15 and 16) and will likely not be implemented in commercial 5G deployments because of technological limitations or because markets are not mature enough to support them. We consider physical layer breakthroughs in Sec. III-A, new architectural and protocol solutions in Sec. III-B, and finally disruptive applications of artificial intelligence in Sec. III-C.

1) Driving Applications behind 6G and Their Requirements:

Traditional applications, such as live multimedia streaming, will remain central to 6G, the key determinants of the system performance will be four new application domains: 1) Multisensory XR Applications: XR will yield many killer applications for 6G across the AR/MR/VR spectrum. Upcoming 5G systems still fall short of providing a full immersive XR experience capturing all sensory inputs due to their inability to deliver very low latencies for data-rate intensive XR applications. A truly immersive AR/MR/VR experience requires a joint design integrating not only engineering (wireless, computing, storage) requirements but also perceptual requirements stemming from human senses, cognition, and physiology. Minimal and maximal perceptual requirements and limits must be factored into the engineering process (computing, processing, etc.). To do so, a new concept of quality-of-physical-experience (QoPE) measure is needed to merge physical factors from the human user itself with classical QoS (e.g., latency and rate) and QoE (e.g., meanopinion score) inputs. Some factors that affect QoPE include brain cognition, body physiology, and gestures. As an example, in, we have shown that the human brain may not be able to distinguish between different latency measures, within the URLLC regime. Meanwhile, in, we showed that visual and haptic perceptions are key for maximizing resource utilization. Concisely, the requirements of XR services are a blend of traditional URLLC and eMBB with incorporated perceptual factors that 6G must support.

Connected Robotics and Autonomous Systems (CRAS): A primary driver behind 6G systems is the imminent deployment of CRAS including drone-delivery systems, autonomous cars, autonomous drone swarms, vehicle platoons, and autonomous robotics. The introduction of CRAS over the cellular domain is not a simple case of "yet another short packet uplink IoE service". Instead, CRAS mandate control system-driven latency requirements as well as the potential need for eMBB transmissions of high definition (HD) maps. The notion of QoPE applies once again for CRAS; however, the physical environment is now a control system, potentially augmented with AI. CRAS are perhaps a prime use case that requires stringent requirements across the rate-reliability latency spectrum; a balance that is not yet available in 5G.

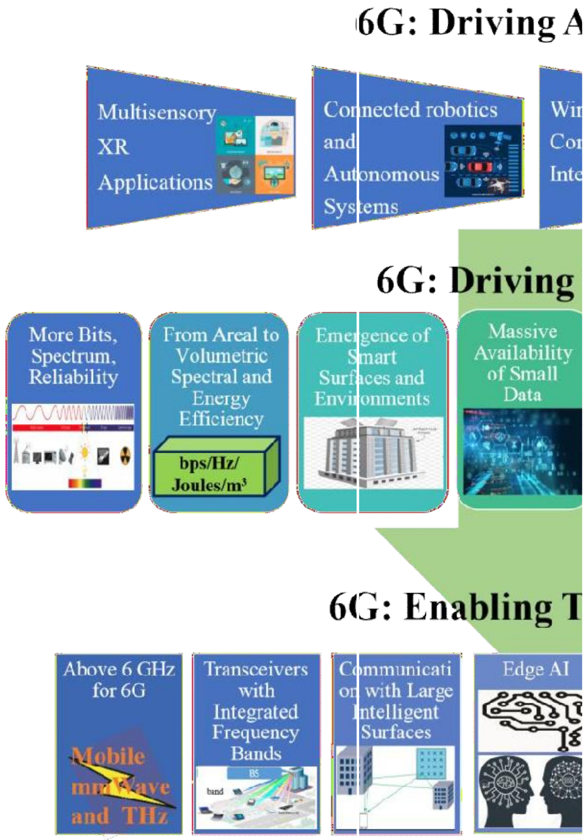

Fig. 1. 6G vision: Applications, t

2) Wireless Brain-Computer Interactions (BCI):

Beyond XR, tailoring wireless systems to their human user is mandatory to support services with direct BCI. Traditionally, BCI applications were limited to healthcare scenarios in which humans can control prosthetic limbs or neighboring computing devices using brain implants. However, the recent advent of wireless brain-computer interfaces and implants will revolutionize this field and introduce new use-case scenarios that require 6G connectivity. Such scenarios range from enabling brain-controlled movie input to fully-fledged multibrain-controlled cinema. Using wireless BCI technologies, instead of smartphones, people will interact with their environment and other people using discrete devices, some worn, some implanted, and some embedded in the world around them. This will allow individuals to control their environments through gestures and communicate with loved ones through haptic messages. Such empathic and haptic communications, coupled with related ideas such as affective computing in which emotion-driven devices can match their functions to their user's mood, constitute important 6G use cases. Wireless BCI services require fundamentally different performance metrics compared to what 5G delivers. Similar to XR, wireless BCI

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services need high rates, ultra low latency, and high reliability. However, they are much more sensitive than XR to physical perceptions and necessitate QoPE guarantees.

3) Blockchain and Distributed Ledger Technologies (DLT):

Blockchains and DLT will be one of the most disruptive IoE technologies. Blockchain and DLT applications can be viewed as the next-generation of distributed sensing services whose need for connectivity will require a synergistic mix of URLLC and massive machine type communications (mMTC) to guarantee low-latency, reliable connectivity, and scalability.

6G: Driving Trends and Performance Metrics:-

The applications of Section II-A lead to new system-wide trends that will set the goals for 6G:

TABLE I: REQUIREMENTS OF 5G VS. BEYOND 5G VS. 6G.

	5G	Beyond 5G	6G
Application Types	eMBB. URLLC. mMTC.	Reliable eMBB. URLLC. mMTC. Hybrid (URLLC + eMBB).	New applications (see Section II-C):MBRLLC. mURLLC. HCS. MPS.
Device Types	Smartphones. Sensors. Drones.	Smartphones. Sensors. Drones. XR equipment.	Sensors and DLT devices. CRAS. XR and BCI equipment. Smart implants.
Spectral and Energy Efficiency Gains[3] with Respect to Today's Networks	10x in bps/Hz/m^2/Joules	100x in bps/Hz/m^2/Joules	1000x in bps/Hz/m^3/Joules (volumetric)
Rate Requirements	1 Gbps	100 Gbps	1 Tbps
End-to-End Delay Requirements	5 ms	1 ms	< 1 ms
Radio-Only Delay Requirements	100 ns	100 ns	10 ns
Processing Delay	100 ns	50 ns	10 ns
End-to-End Reliability Requirements	99.999%	99.9999%	99.99999%
Frequency Bands	Sub-6 GHz. MmWave for fixed access.	Sub-6 GHz. MmWave for fixed access at 26 GHz and 28GHz.	Sub-6 GHz. MmWave for mobile access. Exploration of THz bands (above 300 GHz). Non-RF (e.g., optical, VLC, etc.).
Architecture	Dense sub-6 GHz small base stations with umbrella macro base stations. MmWave small cells of about 100 m (for fixed access).	Denser sub-6 GHz small cells with umbrella macro base stations. < 100 m tiny and dense mm Wave cells.	Cell-free smart surfaces at high frequency supported by mmWave tiny cells for mobile and fixed access. Temporary hotspots served by drone-carried base stations or tethered balloons. Trials of tiny THz cells.

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IV. 6G: RESEARCH AGENDA AND OPEN PROBLEMS

Building on the identified trends in Section II and the enabling technologies in Section III, we now put forward a research agenda for 6G (summarized in Table III).

1) 3D Rate-Reliability-Latency Fundamentals:

Fundamental 3D performance of 6G systems, in terms of ratereliability- latency tradeoffs and SEE is needed. Such analysis must quantify the spectrum, energy, and communication requirements that 6G needs in order to support the identified driving applications. Recent works in provide a first step in this direction.

2) Exploring Integrated, Heterogeneous High-Frequency Bands:

Exploiting mmWave and THz in 6G brings forth several new open problems.

For mmWave, supporting high mobility at mmWave frequencies will be a central open problem. For THz, new transceiver architectures and propagation models are needed. High power, high sensitivity, and low noise figure are key transceiver features needed to overcome the very high THz path loss. Once these physical layer aspects are well-understood, there is a need to develop new network and link-layer protocols to optimize the use of cross-frequency resources while taking into account the highly varying and uncertain nature of the mmWave and THz environments. Another important direction is to study the co-existence of THz, mmWave, and microwave cells across all layers, building on early works such as.

V. 3D NETWORKING

Due to the integration of ground and airborne networks, as outlined in Section III, 6G must support communications in 3D space, including serving users in 3D and deploying 3D base stations (e.g., tethered balloons or temporary drones). This requires concerted research on various fronts. First, measurement and (data-driven) modeling of the 3D propagation environment is needed. Second, new approaches for 3D frequency and network planning (e.g., where to deploy base stations, tethered balloons, or even drone-base stations) must be developed. Our work in showed that such 3D planning is substantially different from conventional 2D networks due to the new altitude dimension and the associated degrees of freedom. Finally, new network optimizations for mobility management, routing, and resource management in 3D are needed.

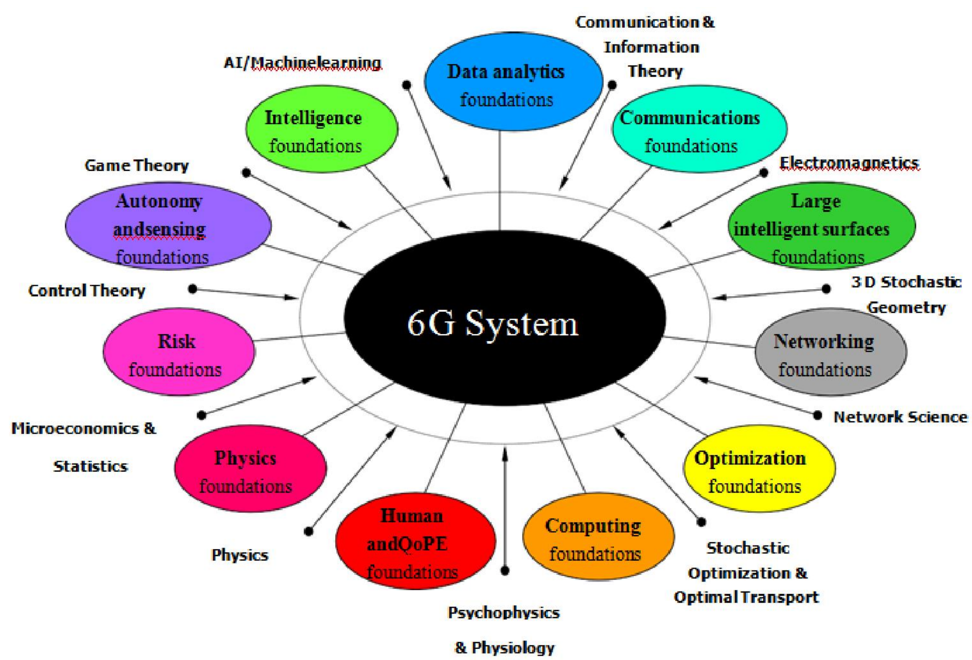

Fig. Necessary foundations and associated analytical tools for 6G.

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Communication with LIS: As per Trend 3, 6G will provide wireless connectivity via smart LIS environments that include active frequency selective surfaces, metallic passive reflectors, passive/active reflect arrays, as well as nonreconfigurable and reconfigurable metasurfaces. Open problems here range from the optimized deployment of passive reflectors and metasurfaces to AI- powered operation of LISs. Fundamental analysis to understand the performance of smart surfaces, in terms of rate, latency, reliability, and coverage is needed, building on the early work in. Another important direction is to investigate the potential of using LIS-based reflective surfaces to enhance the range and coverage of tiny cells and to dynamically modify the propagation environment.

VI. CONCLUSION AND RECOMMENDATIONS

This article laid out a bold new vision for 6G systems that outlines the trends, challenges, and associated research. While many topics will come as a natural 5G evolution, new avenues of research such as LIS communication, 3CLS, holographic radio, and others will create an exciting research agenda for the next decade. We conclude with several recommendations:

- Recommendation 1: A first step towards 6G is to enable MBRLLC and mobility management at high-frequency mmWave bands and beyond (i.e., THz).
- Recommendation 2: 6G requires a move from radiocentric system design (à-la-3GPP) towards an end-to-end 3CLS co-design under the orchestration of an AI-driven intelligence substrate.
- Recommendation 3: The 6G vision will not be a simple case of exploring additional, high-frequency spectrum bands to provide more capacity. Instead, it will be driven by a diverse portfolio of applications, technologies, and techniques.
- Recommendation 4: 6G will transition from the smartphone-base station paradigm into a new era of smart surfaces communicating with human- embedded implants.
- Recommendation 5: Performance analysis and optimization of 6G requires operating in 3D space and moving away from simple averaging towards fine-grained analysis that deals with tails, distributions, and QoPE.

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