JOURNEY FROM 5G TO 6G: LARGE LANGUAGE MODELS TO SMALL LANGUAGE MODELS, ANTENNAS TO FLUID ANTENNA SYSTEMS—A COMPREHENSIVE SURVEY

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Abstract

The introduction of fifth-generation (5G) wireless networks has been a major leap in the field of mobile communications and the networks promise enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). However, a vision of the next decade, the sixth-generation (6G) era, envisions a seamlessly integrated cyber-physical world with such applications as holographic telepresence, pervasive intelligence and the Internet of Everything (IoE). These applications require unprecedented performance requirements that push 5G to its limits. This survey discusses the underlying paradigm shifts needed to get from 5G to 6G. We begin with examining the 5G limitations in terms of the emerging 6G requirements. We then position Artificial Intelligence (AI) not as an application but as a native part of the network architecture with a particular focus on the evolution of Large Language Models (LLMs) to agile and task-specific Small Language Models (SLMs) for network management. In the following we get into the radical change at the physical layer, where we explore the era of the traditional multiple antenna systems and the promising paradigm of Fluid Antenna Systems (FAS) for unprecedented spatial multiplexing and diversity gains. Additionally, we present survey on other key enablers, such as integrated sensing and communication (ISAC), reconfigurable intelligent surfaces (RIS) and terahertz (THz) communication. The aim of this article is to give an overall picture of the most important technological frontiers that characterize the path towards 6G, to point out the synergies, challenges and future research directions.

INTRODUCTION

The International Telecommunication Union (ITU) estimates that by 2030, the global mobile data traffic will be ten times higher, with over half a billion interconnected devices and connectivity forming a fabric of human life and human industry [1]. Although 5G networks are currently being rolled out with disruptive applications at their disposal, they are fraught with inherent energy efficiency, spectral density, and intrinsic intelligence in the face of the 6G vision [2]. The 6G paradigm is aimed at the connection between the digital and the physical world and offering immersive experiences, autonomous systems, and ubiquitous AI services. This needs a radical alteration of network architecture between core and radio edge [3].

The 5G Plateau: A Launchpad for the 6G

Figure 1 illustrates the key performance indicator (KPI) targets of 6G versus 5G which involves 10x improvements in the peak data rate (1 Tbps), 10x reduction in latency (0.1 ms) and 10x improvement in connection density (107 devices/km^2) [4]. The 5G architecture, with the cloud native core and disaggregated RAN has provided a solid foundation. However, its drawbacks are showing up:

1. **AI as an Overlay:** AI and ML are commonly added as an overlay in 5G to accomplish a specific task, such as forecasting loads or managing network slices. 6G needs AI to be a native, integrated capability and a capability to optimize in real-time and evolve on its own [5], [6].

2. **Rigid Physical Layer:** These antenna systems are comparatively fixed although the 5G Massive MIMO is the standard. Further quests toward greater frequencies (e.g. THz) and great spatial efficiency demand greater dynamic and flexible aperture technologies [7].

3. **Siloed functionalities:** The vision of 5G is primarily focused on communication, 6G vision is communication, sensing and computation that can be brought together to form a synergistic network to understand and interact with the surrounding world [8], [9].

These limitations motivate us to explore the core technological shifts that will define the 6G landscape.

6G vs 5G: Key Performance Indicator Comparison

- 5G: 20 Gbps, 1 ms, 10^6/km², 1x, 1x, 99.999%
- 6G: 1 Tbps, 0.1 ms, 10^7/km², 100x, 3x, 99.9999%
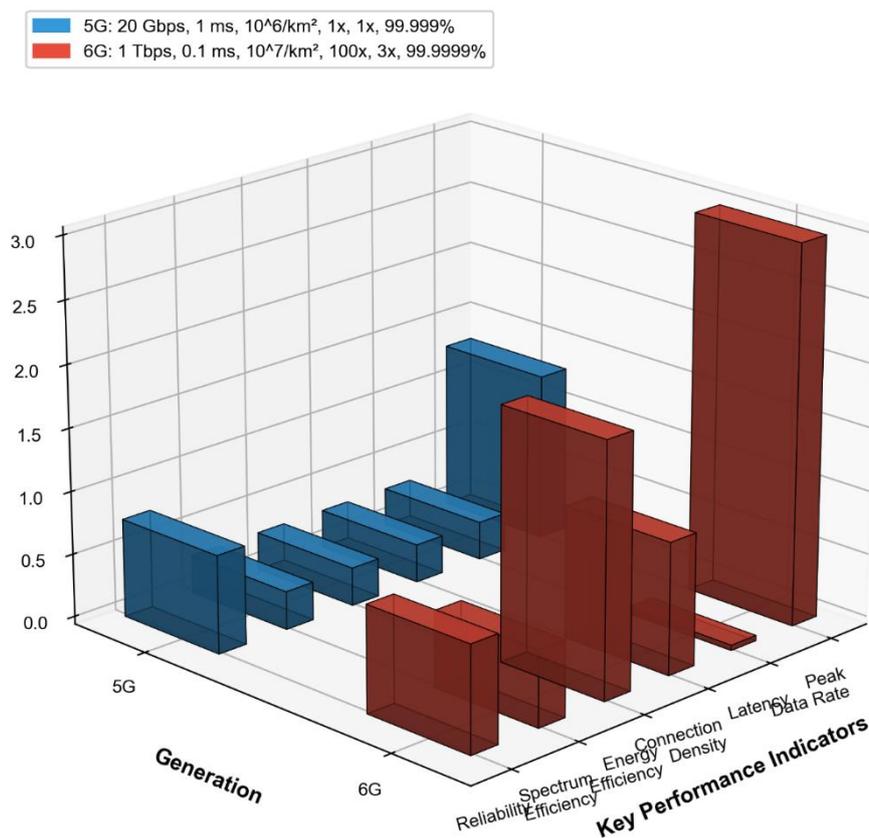
Towards a Native-AI and Hyper-Connected 6G Era

What if the network could learn, adapt and self-optimize in real-time? What if there was a way to change the shape and position of the antenna so that it perfectly tracks a user? This would have the advantage of revolutionizing reliability, spectral efficiency, and energy consumption. The positive characteristics of such a 6G network are:

1. **Context-Awareness:** The network would have a situational understanding and it

would be able to predict the traffic patterns and user mobility [10] [11].

2. **Zero-Energy Devices:** Pervasive connectivity might be realized for battery-free sensors, via sophisticated ambient backscattering by leveraging the 5G IoT building blocks [12], [13].

3. **Pervasive Trust:** Trust is built-in Native AI would provide intrinsic security through the use of anomaly detection and adaptive cryptographic protocols [14].

Previously, large AI models had too high a computational burden to be implemented in network elements with limited resources. However, the advent of Small Language Models (SLMs), which retain a substantial proportion of the capability of LLMs at a fraction of the size and cost, makes embedded intelligence possible [15], [16]. Similarly, the idea of Fluid Antenna Systems (FAS), where a port can change its location between several predetermined positions, promises a revolution in spatial diversity, which overcomes limitations of the traditional arrays [17], [18]. This survey discusses these game-changing technologies on the road to 6G.

Survey Taxonomy: 6G Technological Evolution
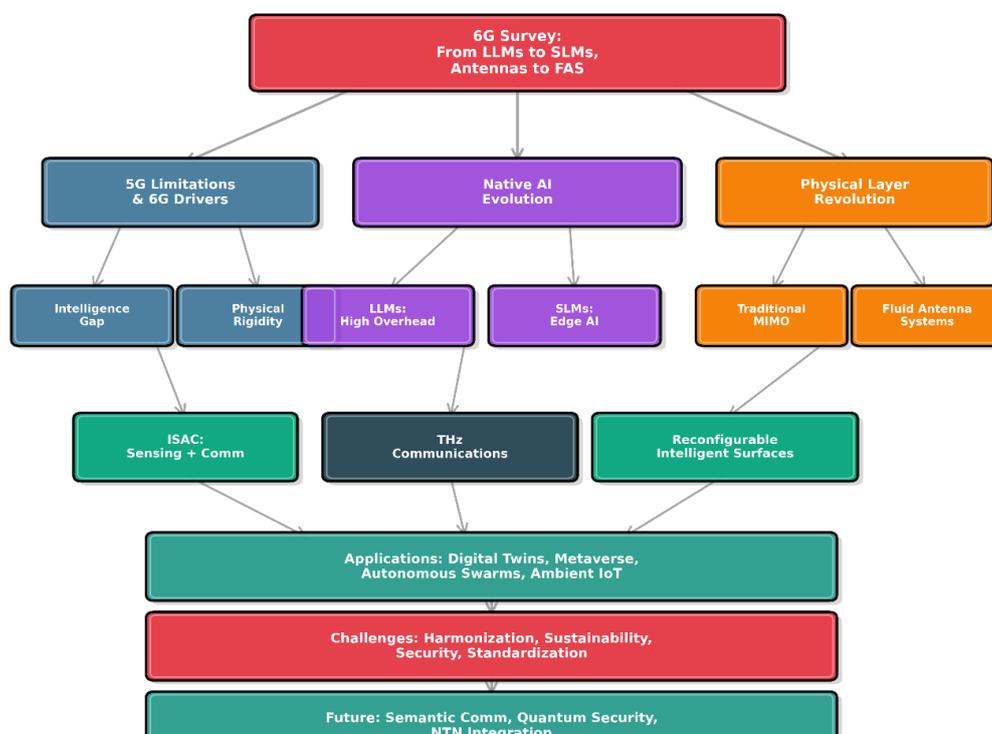
Our work organization examines the 6G journey with a focus on the interaction between architectural intelligence and physical layer innovation, which may be appropriate to realize the future hyper-connected society. Figure 2 shows a taxonomy of our survey paper. Precisely, the following aspects are covered in this article:

● We discuss the limitations of 5G and driving forces behind 6G.

● we introduce the evolution from Large Language Models (LLMs) to Small Language Models (SLMs) in native AI in networks.

● We show how to get from the traditional antennas to Fluid Antenna Systems (FAS).

● We elaborate the potential enablers, such as Integrated Sensing and Communication (ISAC) and Terahertz (THz) bands.

● We demonstrate potential 6G applications, its challenges and future research directions. The rest of the article is structured as follows.

The rest of the article is structured as follows. Section 2 is dedicated to the driving requirement and limitations of 5G. The

advancement of indigenous AI from LLMs to SLMs is discussed in Section 3. Section 4 reveals the revolution in the physical layer, with a focus on FAS. The integration between sensing and communication is discussed in Section 5. Section 6 casts the issue of THz communications and Reconfigurable Intelligent Surfaces (RIS). Some of the potential uses of 6G are illustrated in Section 7. The challenges and future directions are presented in Section 8. Finally, the paper is concluded with Section 9.

2. 5G Limitations and 6G Drivers—The Need for a Paradigm Shift

The spectacular results of 5G in improving the mobile broadband and facilitating critical Internet of Things (IoT) communications have set a new benchmark for wireless communications [19], [20]. However, the envisioned paradigm of 6G - including tactile holography, autonomous swarm robotics and embodied artificial intelligence - requires a fundamental rethinking of the main principles of network design [21]. The prevailing 5G architecture is powerful, however, a common design limitation of current communication paradigm in terms of spectrally inefficient, energy consumption, and computational overhead hampers 5G's capability to meet the 6G Key Performance Indicators (KPIs) [22]. We will discuss these limitations in the first part of the study from the point of view of native intelligence, physical layer flexibility and functional synergy, and then we will go over the driving forces that will require the transition to 6G.

2.1. The Intelligence Gap—An AI-Native Perspective

In 5G networks, Artificial Intelligence and Machine Learning (AI/ML) are mainly implemented as external applications or management plane applications for functions such as network slicing orchestration [3] and predictive resource allocation [23]. This overlayed approach adds latency and in many cases also depends on centralized cloud resources, which is not compatible with the real-time and distributed decision-making that is needed in 6G scenarios. For example, control of ultra-dense network with millions of devices per square kilometer or sub-millisecond latency of

vehicle-to-everything (V2X) on demand needs intelligence to be well embedded in the network fabric itself [3], [24]. The existing disconnect between the protocols used to communicate and the artificial intelligence models that operate on them leaves an "intelligence gap," where the network responds to changes instead of adapting to them in advance.

2.2. Physical Layer Rigidity—A Spectral Efficiency Perspective

Massive Multiple-Input Multiple-Output (MIMO) has been one of the pillars of 5G offering substantial improvements in capacity and link reliability [25], [26]. However, conventional MIMO systems have fixed antenna positions and form factors. The quest for higher data rates is leading to the use of higher operation frequencies up to the Terahertz (THz) band where the wavelengths are very short and the path loss is severe [27], [28]. At these frequencies, performance of traditional MIMO is seen to be limited by the correlation of antenna elements in space and their physical sizes of devices. Furthermore, the present-day method of beam management and handover results in a substantial signal overhead. A more fluid and dynamic technology for antennas is needed to overcome these challenges and deliver the order of magnitude improvement in spatial multiplexing and energy efficiency envisioned for 6G [29], [30].

2.3. Functional Silos—A Synergy Perspective

The 5G networks are developed for data commutation mainly. While Non-Terrestrial Networks (NTN) and positioning services were anticipated as part of the 5G standard, sensing and communication have been developed mainly as two separate systems, which results in an inefficient exploitation of spectrum and hardware resources [31]. The 6G vision of integrated sensing and communication (ISAC) calls for a holistic design approach where the same waveform and hardware infrastructure can be used at the same time to perform high-resistance sensing (e.g., imaging, gesture recognition) and high-rate data transfer [32], [33]. This synergy is important in use cases such as autonomous navigation where a single system must both communicate with other vehicles and perceive the environment with high precision

and avoid the cost and weight in addition to spectrum conflict of two systems.

Discussion: In Section 2, the main limitations of 5G that serve as the drivers for 6G research and development are summarized in Table 1. Various steps are being taken to address these gaps some of which are discussed below.

1. **AI-Native Architectures:** The integration of AI as a fundamental building block instead of an add-on, is being investigated to allow for zero-touch network and service management (ZSM) and real-time radio resource control [34], [35].

2. **Fluid Antenna Systems (FAS):** FAS are becoming a new disruptive technology to address the spatial limitations the traditional MIMO suffers from, particularly at higher frequencies, by allowing for dynamic aperture reconfiguration [36], [37].

3. **Integrated Sensing and Communication (ISAC):** ISAC is in a process of standardization to eliminate the functional silos and to be able to share the spectrum and infrastructure between the communication and radar-like sensing functions, opening doors for joint perception and communication networks [38], [39].

Table 1. Summary of 5G limitations and 6G drivers.

Subsections	Key Points
The Intelligence Gap	• AI in 5G is an overlay, leading to latency and centralized processing. • Inability to support real-time, distributed decision-making for 6G KPIs. • Creates a reactive, rather than proactive, network.
Physical Layer Rigidity	• Conventional MIMO is limited by fixed antenna structures. • Performance is constrained at THz frequencies due to spatial correlation and size. • High signaling overhead for beam management.
Functional Silos	• Communication and sensing are largely separate systems in 5G. • Inefficient use of spectrum and hardware resources. • Hinders the development of synergistic applications like autonomous navigation.

3. The Evolution of Native AI: From Large Language Models to Small Language Models

This massively elevated expectation placed on the self-sustaining, adaptive and intelligent ecosystem called 6G [40] calls for a down-to-the-essence redesign of the network in which AI is embedded. There has been a huge hype in generative AI using the Large Language Models (LLM) with hundreds of billions of parameters, exhibiting excellent language understanding and content creation skills [40], [41]. However, their massive computational requirements, inference latency and energy consumption make them unwilling for deployment at the network edge or in resource constrained network functions. The paradigm is thus changing to the development and use of Small Language Models (SLMs) - compact, efficient, and specialized models capable of bringing powerful AI capabilities directly into the radio access network (RAN), core network, and end-user devices [16], [42].

3.1. Understanding Large Language Models and their Overhead

Language models (LLMs), like GPT and Llama families, are Transformer-based language model and are trained on massive text and code corpora [43], [44]. Their power comes from their emergent capabilities - the capabilities that are not specifically programmed into them but instead learned from data (for example, complex reasoning and problem solving). Table 2 lists the development of representative LLMs with an increasing number of parameters.

However, network integration has a high price to pay for this power [45]:

1. **Computational Intensity:** Inference with a large model is computationally intensive, which is not available at the base stations or user equipment (UE) [46].

2. **Memory Footprint:** Storing model weights (often hundreds of gigabytes) is impractical for edge devices [43].

3. **Inference Latency:** Due to the sequential nature of text generation, the latency of this inference is high, contradicting response times below one millisecond required by numerous 6G control loops [47], [48].

4. **Energy Consumption:** The amount of energy frequently required for an inference can be orders of the magnitude greater than what may be achievable for battery-powered IoT devices [49].

These shortcomings make it unsuitable for general-purpose LLMs to be used for real-time network control, which is why we decided to investigate their smaller and more efficient relatives [43].

Table 2. Training of Representative Language Models.

S.No	Period	Model	Parameter Count	Key Characteristic
1	2018	BERT	110M - 340M	Bidirectional encoder, revolutionized NLP tasks.
2	2020	GPT-3	175B	Demonstrated strong few-shot learning capabilities with a decoder-only architecture.
3	2023	LLaMA 1	7B - 65B	Open-source models showing state-of-the-art performance with fewer parameters.
4	2023	GPT-4	~1.7T (estimated)	Multimodal capabilities, improved reasoning and accuracy.
5	2024	LLaMA 2 / 3	7B - 70B	Optimized for dialogue and instruction-following; widely used for on-device applications.
6	2024	Phi-3	3.8B	A "SLM" class model, rivaling larger models' performance, designed for mobile deployment.

3.2. The Rise of Small Language Models

Small Language Models (SLMs) have a number of parameters in the range of several hundred million to 7 billion. They are not just smaller versions of LLMs: they are usually trained using more targeted and high-quality datasets and advanced training techniques such as knowledge distillation from larger models [50], [51]. The advantages of SLMs for 6G are as follows:

1. **On-Device Deployment:** SLMs with 3-7 billion parameters are effectively executed on current smartphones and edge servers to allow application of local intelligence [52].

2. **Low Latency Inference:** They are smaller and hence can be processed faster to satisfy the stringent latency constraints of radio resource management[53].

3. **Energy Efficiency:** SLMs become possible because the computational requirements are drastically lower due to lower ranges of the devices and network elements they interface with [54].

4. **Task Specialization:** SLMs have fine-tuning to certain tasks in network management e.g. predicting channels, noting anomalies or selecting a beam, but can perform those tasks with higher accuracy than a generic LLM [16], [50].

3.3. SLMs for Radio Resource Management and Network Optimization

In addition, the use of SLMs in 6G will transform traditional network operations. An interesting way forward is to make SLMs smart controllers which use networking state information (e.g., CSI, traffic load, QoS requirements) as input and configuration parameters which are optimal or near-optimal. For example, an SLM can be programmed for:

● **Beam Management and Prediction:** An SLM is able to forecast user movement and preemptively change FAS ports or remake beamforming weights and minimize

overheads and process handover success rates [55], [56].

● **Dynamic Spectrum Access:** An SLM can acquire intricate spectrum occupancy patterns and make real-time spectrum sharing decisions in cognitive radio networks that outperforms the conventional sensing-based schemes [57], [58].

● **Network Slicing Orchestration:** SLM has the capability to orchestrate the life cycle of network slices by dynamically allocating resources according to the predicted service demand and SLA requirements [59], [60].

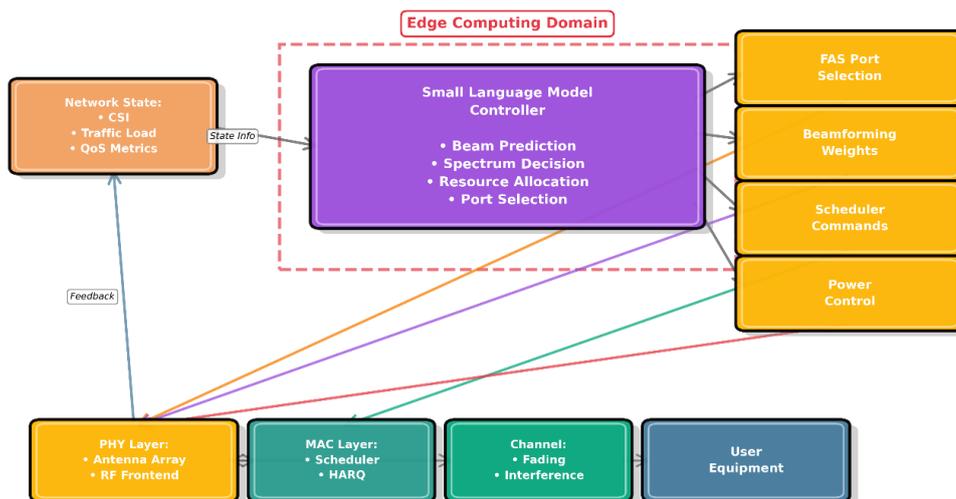## SLM-Based Intelligent Controller for 6G RAN

Figure 3 shows a conceptual architecture where the SDR controller based on SLM is applied at the edge and it communicates with the PHY and MAC layers, giving smart control signals to FAS, scheduler, and power amplifier.

Discussion: Table 3 gives the transition from LLMs to SLMs in the context of 6G. The key points are as follows:

1. LLMs have a wide capability, but limited to high computational overhead, memory footprint, and latency which render them incompatible with direct integration into network functions with time sensitivity [40], [48].

2. The smaller size and more focused training of SLM allow for on-device and edge intelligence which is fundamental for the low latency and energy efficient operation of 6G networks [16], [61].

3. SLM can be specifically tailored to perform important radio resources management functions such as beam prediction [62], [63] and dynamic spectrum access [6], [64] to result in more efficient and autonomous network operation.

Table 3. Summary of LLMs vs. SLMs for 6G.

Aspect	Large Language Models (LLMs)	Small Language Models (SLMs)
Parameter Scale	10s of Billions to Trillions	100s of Millions to 7 Billions
Deployment	Centralized Cloud	Edge, Device, Network Element
Inference Latency	High (seconds to minutes)	Low (milliseconds)
Energy Consumption	Very High	Moderate to Low
Primary Strength	General-purpose reasoning, content creation	Task-specific optimization, real-time control

Suitability for 6G	High-level network planning, code generation for protocols	Real-time RAN control, UE intelligence, distributed optimization

4. The Physical Layer Revolution: From Antennas to Fluid Antenna Systems

The continuous demand for increasing data rate and connection density is raising the limits of the physical (PHY) layer in the 6G networks. While Multiple-Input Multiple-Output (MIMO) and its massive extension have been playing a pivotal role in 5G, they are essentially limited by stationary positions of the antenna elements [65]. This rigidity constrains the degrees of freedom that can be used by spatial multiplexing and diversity particularly in devices with size constraints and higher frequencies where wavelengths are smaller [66]. A paradigm shift is happening: a shift away from conventional antennas with fixed apertures to Fluid Antenna Systems (FAS) - a technology that serves a new dimension of reconfigurability, by dynamically switching the effective radiating point of the antenna between a set of predefined locations [36], [67].

4.1. Understanding Fluid Antenna Systems (FAS)

The fundamental concept of FAS is to decouple a radio frequency (RF) chain and one, fixed antenna element. Instead, a single RF chain is coupled to a switching network able to dynamically select one of N possible port locations of a given fluid antenna structure such as a linear array or surface-based array [68], [69]. This is conceptually shown in figure 4a. The key innovation is to take advantage of the large variation of the wireless channel in space, over distances small as half a wavelength. By smarter choice of the port with the best channel condition (e.g. highest signal-to-interference-plus-noise ratio, SINR), the system can realize exceptional diversity gains [70].

The operation principle of a basic FAS can be explained as follows:

1. **Channel Probing:** The FAS receiver probes channel conditions at some or all of its N available ports for a short period of time [71].
2. **Port Selection:** An intelligent controller (with possibly the help of an SLM as mentioned in Section 3) selects the best port maximizing some utility function (e.g. SINR or capacity) [72].
3. **Switch Configuration:** A fast RF switch connects the single RF chain to the selected port [73].
4. **Communication:** This type of communication is done via this optimally selected port for the length of a coherence time block [74].

This process enables the antenna "to move its location" in such a way that it can follow the spatial maxima of the electromagnetic field, which is an effective tool to fight with problems of fading and interference with relatively small hardware complexity [75], [76] .

4.2. FAS Architectures and Configurations

The implementation of FAS can be divided according to the structure of the fluid antenna and the switching mechanism.

4.2.1. One-Dimensional Fluid Antenna Systems

The first and most investigated schemes is the 1D FAS which N ports are configured along a linear dimension, e.g. a meandering line or a straight waveguide [36]. This critical design parameter is the length of this structure, W which can be expressed in wavelengths. A larger W gives a larger spatial range of choice of ports, and so larger diversity gains are possible. A 1D FAS with N=5 ports is shown in Figure 4b. This type is especially suitable for integration in the edges of mobile devices.

4.2.2. Two-Dimensional and Surface Fluid Antenna Systems

To realize even more spatial diversity, 2D FAS makes the concept spread over a surface by arraying ports in a grid-like manner [67], [77]. This makes it possible for the system to take advantage of the channel variations in two dimensions, which is particularly useful in rich scattering environments. The surface area is then the key parameter. This design is also known as a Liquid Antenna or spatially reconfigurable aperture and has potential to be used in the device casings or intelligent surfaces.

Figure 4. Conceptual Diagrams of Fluid Antenna Systems.
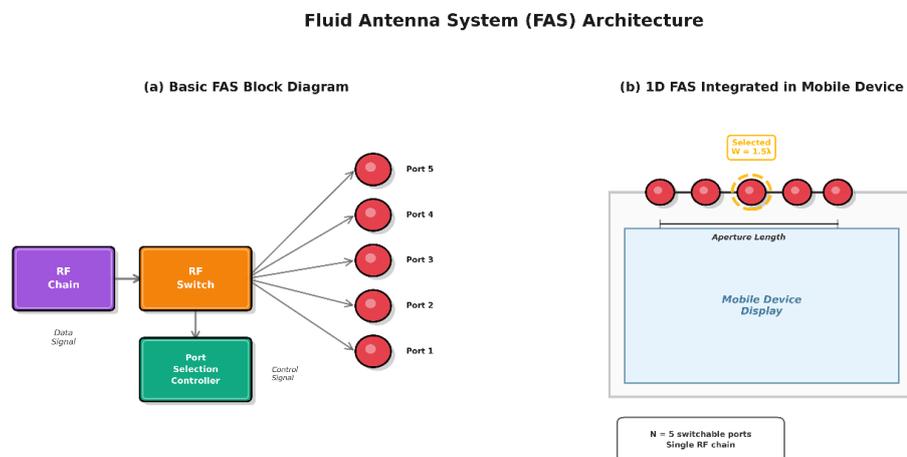
(a) Basic block diagram of an FAS with a single RF chain connected via a switch to N ports on a fluid antenna structure.
(b) An example of a 1D FAS integrated into a mobile device, with 5 potential port locations along the top edge.

4.2.3. FAS with Multi-Port Selection

While the initial work is based on connecting one RF chain to one port at a time, advanced architectures are looking into the use of multiple RF chains that can be simultaneously connected to multiple ports [70]. This results in a dynamic MIMO system in which the effective antenna array configuration can be tailored dynamically to the channel conditions in such a way that the advantages of FAS may be combined with the multiplexing gains of MIMO [78].

4.3. Performance Gains and Trade-offs

Theoretical and experimental research has shown the great potential of FAS. Authors showed that a 1D FAS with size of W=1.5 λ and N=20 ports can achieve an outage probability of $10^{\wedge}(-5)$ at an SNR where a single antenna system has an outage of $10^{\wedge}(-1)$ [1][69] [79]. This is a diversity order that is in effect equivalent to having hundreds of traditional antennas.
The primary trade-offs involve:
● **Switching Complexity:** A fast low loss RF switch and a port selection control is needed [69].

● **Channel Estimation Overhead:** N ports have to acquire channel state information (CSI) on each of them, which can be a source of overhead. Techniques of compressed sensing and port prediction are being explored to reduce this [80] .
● **Aperture Size:** There is a direct relationship between the performance improvement and the electrical size W of the fluid antenna that may be limited by the form factor of the device [30].

Discussion: Table 4 summarize the key aspects of FAS and its comparison to traditional MIMO. The major points are the following:
1. FAS adds a new level of freedom by permitting one RF chain to take advantage of spatial diversity by dynamically selecting the port, and it overcomes the limitations caused by fixed antenna systems [69].
2. The architecture can be scaled up from 1D linear structures to 2D surfaces with the possibility of the multi-port selection to combine diversity and multiplexing gains [30], [70] .
3. The performance improvements in terms of outage probability and diversity order are quite high, up to the performance of massive MIMO using a single RF chain, albeit within a limited aperture [69], [70], [81].
4. The major challenges are designing efficient switches, channel estimation overhead and integration in small form factor devices [82].

Table 4. Summary of Fluid Antenna Systems (FAS).

Aspect	Traditional MIMO	Fluid Antenna System (FAS)
Core Principle	Spatial multiplexing/diversity using multiple fixed antennas and RF chains.	Exploiting spatial channel variation by dynamically switching a single (or few) RF chain(s) among N ports on a fluid aperture.
Hardware Complexity	High (multiple RF chains, ADCs/DACs).	Lower in RF chains, but introduces complexity of RF switching network and port selection controller.
Spatial Flexibility	Fixed. Performance limited by antenna spacing and correlation.	High. The effective antenna "location" can be adapted to the instantaneous channel conditions.
Key Performance Gain	Multiplexing gain (capacity), array gain.	Extreme diversity gain, interference mitigation.
Suitable For	Base stations, devices with sufficient space.	Size-constrained devices (UEs, IoT sensors), especially at high frequencies (mmWave, THz).
Main Challenge	Cost, power consumption, and form factor for many RF chains.	Switching loss, channel estimation overhead for multiple ports, aperture size constraint.

The Fusion of Functions: Integrated Sensing and Communication (ISAC)

The classical architecture of the wireless network has considered communication and sensing as two different systems that have different purposes, devices, and frequency ranges. Communication systems are made to guarantee that information is shared in physical dependability, whereas sensing systems (e.g., radar, LiDAR) are planned to derive information on the environment, e.g. the range, velocity, and angle of an object. Such separation causes cost, hardware and spectral inefficiencies. The 6G vision dismantles these silos with a paradigm of Integrated Sensing and Communication (ISAC), in which a single system is used to do high-rate data communication and high-resolution environmental sensing at the same time, this time using the same waveform, hardware, and spectrum [32], [83]. One of the pillars of facilitating the context-aware, interactive applications of the 6G era is this synergy.

5.1. The ISAC Paradigm and Its Drivers

ISAC converts the wireless network into a passive data pipe to an active perceptual organ. The ISAC driving forces in 6G are:

1. **Spectrum Efficiency:** Since spectrum is a limited resource, ISAC enables the simultaneous utilization of the allocated bands (e.g., cellular bands) between communication and sensing (e.g., radar functions do not have to be assigned specific spectral segmentation) [33], [39], [84].

2. **Hardware and Cost Efficiency:** One ISAC platform will also avoid the redundancy of RF components (antennas, power amplifiers, mixers) and signal processing units, which can lead to the lowering of the total cost, size, and power usage of devices and infrastructure [85], [86].

3. **Native Context-Awareness:** ISAC allows the network to have a natural cognizance of its surroundings. It is able to detect the whereabouts and movement of users and objects to be able to allocate resources proactively, improve security and introduce new application paradigms [87], [88].

4. **Mutual Benefits:** The dense infrastructure of communication networks (e.g., cell towers to support cooperative sensing) can be utilized by sensing, and the precise environmental knowledge that sensing can offer can be used by communication (e.g., predictive beamforming based on the location of sensed objects)[89].
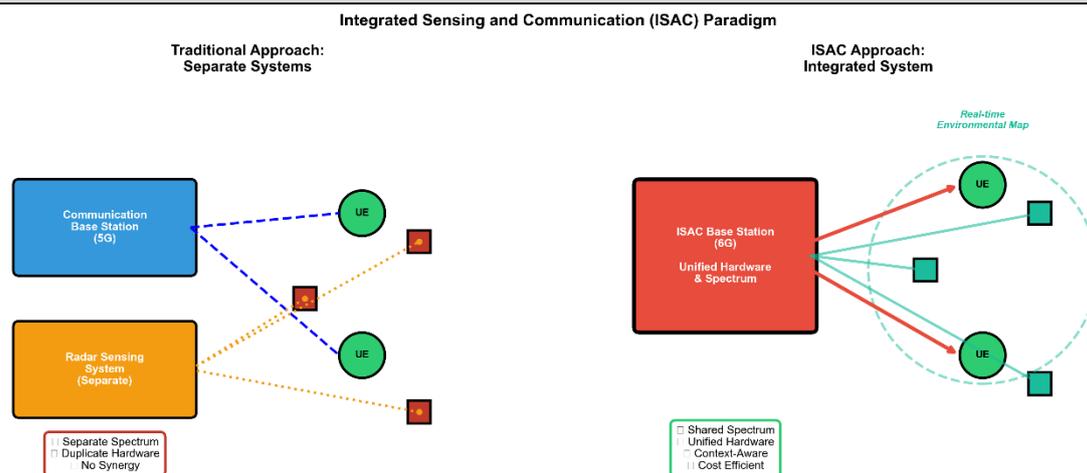
Figure 5. The ISAC Paradigm Shift.

(Left: Traditional separate systems for communication and radar sensing. Right: An integrated ISAC base station that simultaneously serves users and creates a dynamic environmental map.)

Figure 5 shows how there is conceptual transformation of distinct systems into an integrated ISAC architecture, in which a base station (BS) also supports communication users as well as produces a sensing-centric perception of its coverage zone.

5.2. ISAC Waveform Design and Signal Processing

The waveform is the core of an ISAC system that is required to meet the twofold goals of data transmission and target parameter estimation. A number of waveform candidates are under investigation, all with trade-offs.

5.2.1. Communication-Centric Waveforms

The latest standard, Orthogonal Frequency-Division Multiplexing (OFDM) which is the foundation of 4G and 5G is a natural choice because it is compatible by nature with existing standards. The sensing can be done via the analysis of the perturbations in the received signal that is carried by the environmental objects in the received OFDM signal [90], [91]. The information (Channel State Information and reference signals) needed to communicate can be reused to sense. The benefit is little modification of the communication standard, but the performance of sensing (e.g. resolution, ambiguity) can be sub optimal relative to the dedicated radar waveforms.

5.2.2. Sensing-Centric Waveforms

Frequency-Modulated Continuous-Wave (FMCW) based on traditional radar waveforms still provide an excellent performance in sensing, including high range-resolution and automatic resistance to interference. It is being researched to incorporate communication data into the FMCW signal, such as by varying the length of the chirp, the initial phase or frequency offset [92]. Although this method has the advantage of offering better sensing quality, it can be very demanding in terms of making changes to the receiver design of the communication and can be quite difficult to reach very high data rates.

5.2.3. Jointly Designed Waveforms

The most promising path of 6G is the joint design of fully new waveforms with the best functions in both directions. It includes the optimization problem involving tradeoff between communication measures (e.g., spectral efficiency, Bit ErrorRate) and sensing measures (e.g., CramerRao Bound for parameter estimation, ambiguity function) [93]. The objective of these waveforms is to attain a performance frontier that cannot be attained

either by communication- or sensing-centric waveforms itself.

Figure 6 also shows that the signal processing chain in an ISAC receiver is more complicated. It is required to isolate and collectively decode data of communication whilst at the same time estimating sensing parameters of the same received signal and in many cases with mutual interference.
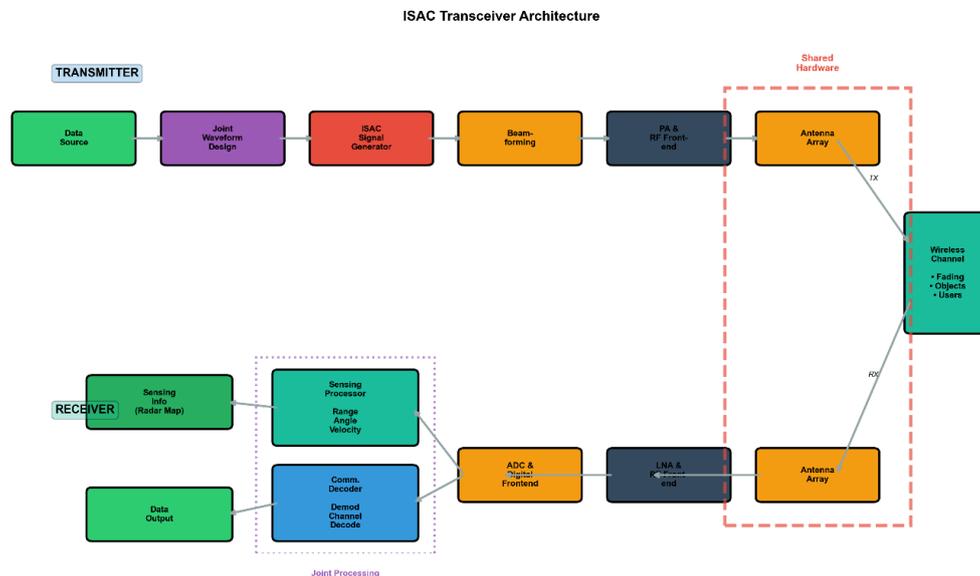

Figure 6. Simplified ISAC Transceiver Signal Processing Chain.

(A block diagram showing a single transmitter generating a joint ISAC waveform, and a receiver with parallel processing chains for data decoding and sensing parameter estimation, highlighting shared components like the antenna array and ADC.)

5.3. ISAC Applications and Use Cases

With the merge of the sense and communication, the number of new applications opens so widely:

● **High-Accuracy Localization and Tracking:** ISAC is capable of centimeter-level precision in the positioning of devices and objects in-the-field and out-of-the-field, a hundredfold better than GNSS or 5G positioning, and makes it possible to perform advanced logistics and augmented reality [94].

● **Gesture and Activity Recognition:** ISAC has demonstrated the

ability to identify human gestures, activities and even vital signs (breathing, heartbeat) without cameras or wearable sensors by analyzing the micro-Doppler and reflection pattern of wireless signals, improving smart home and health care applications [95], [96].

● **Autonomous Vehicle Networks:** AVs and roadside units can also communicate with each other (V2X) and with non-connected things such as pedestrians, bicycles and obstacles, which forms a complete picture of perception that promotes safer autopilot movements [97], [98].

● **Integrated Sensing and Communications in 6G (ISAC-6G):** Sensing will be a 6G RAN native service that enables network operators to provide industry 4.0, smart cities, and environmental monitoring, Sensing-as-a-Service[33], [89].

Discussion: Table 5 summarizes the key aspects of ISAC. The main points are as follows:

1. ISAC is an essential change of the segregated systems to an integrated platform that simultaneously does the communication and sensing, resulting in spectrum, hardware and cost efficiency gains [33] .

2. Waveform design is a highly important study field, where there are tradeoffs between exploiting existing communication waveforms (e.g., OFDM) [99], [100], [101], adaptation of sensing waveforms (e.g., FMCW) [93], and new jointly optimized waveforms [100].

3. ISAC supports a new generation of context applications, not only high-accuracy positioning [102] or gesture recognition [102] but also improved autonomous systems [103] , and is a primary enabler to the 6G ecosystem.

Table 5. Summary of Integrated Sensing and Communication (ISAC).

Aspect	Traditional Separate Systems	Integrated Sensing and Communication (ISAC)
Design Philosophy	Siloed optimization: communication for data rate, sensing for accuracy.	Joint optimization: a single system fulfills both functions.
Hardware & Spectrum	Dedicated hardware and spectrum for each function, leading to inefficiency.	Shared hardware and spectrum, leading to reduced cost, size, and improved spectral efficiency.
Core Waveforms	Communication: OFDM. Sensing: FMCW, Pulse Radar.	Evolving from adapted OFDM/FMCW to novel, jointly designed waveforms.
Network Capability	The network is a data pipe.	The network is an active perceptual system with inherent context-awareness.
Key Applications	Separate: Mobile broadband + standalone radar/LiDAR.	Fused: Centimeter-level positioning, gesture recognition, autonomous navigation, Sensing-as-a-Service.
Main Challenge	Inefficient resource usage, lack of synergy.	Waveform design, signal processing complexity, managing interference between functions, standardization.

6. Pushing the Extremes: Terahertz Communications and Reconfigurable Intelligent Surfaces

The search of the terabit-per-second data rates and near-instantaneous connectivity that is expected to come with 6G requires the search of new spectral and spatial dimensions. The two technologies that have the potential to be transformative are Terahertz (THz) communication that opens up vast new bandwidths and Reconfigurable Intelligent Surfaces (RIS), which opens up new levels of control over the very environment of wireless propagation [104], [105]. Thz considers a spectral frontier and RIS considers a spatial frontier. These two combined are a symbiotic pair, since the extreme propagation issues of the THz band can be reduced with the smart manipulation of waves by RIS.

6.1. Terahertz (THz) Band Communication: The Bandwidth Frontier

A huge supply of continuous bandwidth, tens or hundreds of GHz of it, is provided by the Terahertz band, approximately 0.1 THz to 10 THz, and is the most straightforward route to Tbps-scale data rates [106], [107]. This is the first change since the jammed sub-6 GHz and millimeter-wave (mmWave) bands of 5G.

6.1.1. Opportunities and Potential Gains

The bandwidth is the major benefit of the THz band. According to Shannon Hartley theorem, the capacity of a channel directly depends on bandwidth. This enables very high data rates even using fairly simple modulation schemes. Key applications include:

● **Wireless Backhaul/Fronthaul:** Ultra-high-speed links between base stations [108], [109] .

● **Kiosk Downloading:** Instant downloading of ultra-high-definition material in seconds [110], [111].

● **Intra-Chip and Inter-Device Communication:** This facilitates wireless communication inside of computing systems and among devices that are at close proximity to one another [112], [113].

Figure 7a shows how staggering is the available bandwidth at the THz band as compared to lower frequency bands.
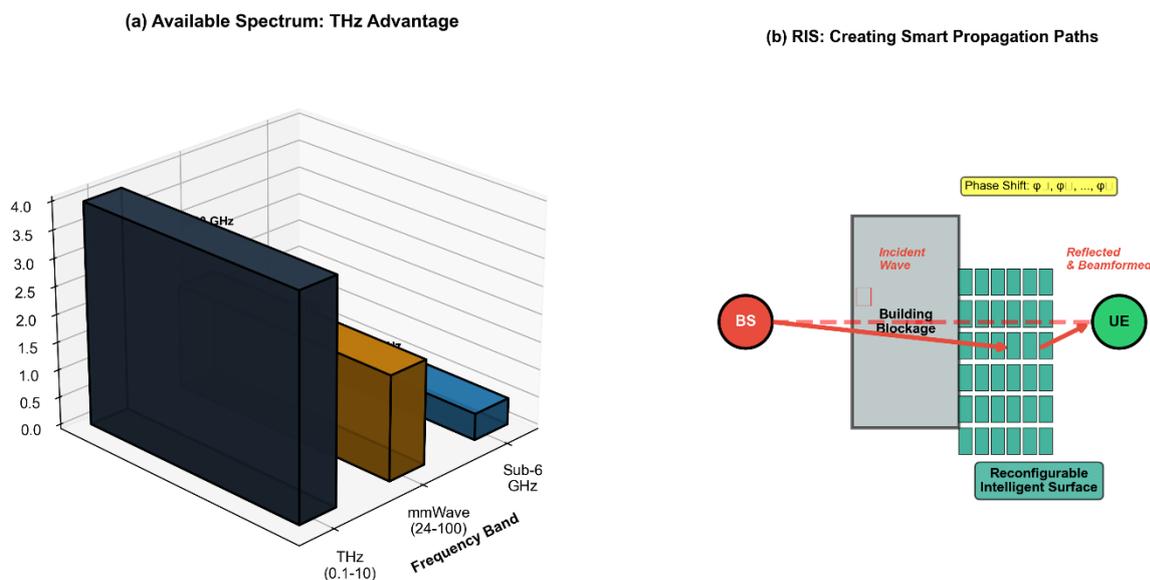
Terahertz Communications & Reconfigurable Intelligent Surfaces

Figure 7. The Extremes of 6G.

(a) A comparative chart showing the available contiguous bandwidth in the THz band dwarfing the combined bandwidth of all lower-frequency bands (Sub-6 GHz, mmWave). (b) An illustration of an RIS mounted on a building facade, dynamically reflecting signals from a base station to a user equipment, effectively creating a smart reflector to bypass an obstruction.)

6.1.2. Fundamental Challenges and Mitigation Techniques

Nonetheless, the THz communications are burdened with severe difficulties that should be overcome:

High Propagation Loss: THz propagation is associated with extreme free-space path loss and, most importantly, extreme molecular absorption loss because of water vapor and oxygen in the atmosphere [114]. This means that the communication range will be very low, usually tens of meters.

1. **Blockage and Scattering:** THz signals do not penetrate well past structures such as walls and even human bodies. They also are

easily scattered by tiny particles such as dust and rain [114], [115].

2. **Hardware Imperfections:** It is difficult to design efficient transceiver THz-level devices

with high power. Other components such as power amplifiers, mixers and antennas are not mature and have high power consumption and cost [116].

Mitigation strategies include:

● **Ultra-Massive MIMO (UM-MIMO):** The utilization of very massive antenna arrays to produce very narrow beams, which are of high gain and capable of compensating the high path loss [65], [82].

● **Intelligent Reflecting Surfaces:** RIS can be applied in an attempt to traverse other non-line-of-sight (NLoS) paths and widen the coverage, and this is detailed in the following subsection [117], [118].

● **Advanced Signal Processing:** New algorithms should be developed to do beam alignment, channel estimation and equalization that considers the specialized features of the THz channel [28], [115].

6.2. Reconfigurable Intelligent Surfaces (RIS): The Smart Radio Environment Paradigm

A Reconfigurable Intelligible Surface (RIS) is a planar material made by a huge number of passive, inexpensive components (e.g., metamaterials) the electromagnetic qualities of which (amplitude and phase of the reflected signal) can be dynamically programmed in software [119], [120]. In contrast to traditional relays, an RIS reflects the signals without the need of power amplifiers and complicated signal

processing and is an energy-efficient way to shape the radio environment.

6.2.1. Working Principle and Architecture

The main principle of an RIS is to add a phase shift to an incident wave under a controlled condition and reflect it. The RIS is capable of controlling the phase shift of each of the elements separately and therefore can focus the reflected signal to a desired receiver, or form a signal null at an interferer [120] as illustrated in Figure 7b. The architecture usually comprises of:

● **Metasurface Layer:** Here the tunable components (e.g., PIN diodes, varactors).

● **Control Circuitry:** This is a basic microcontroller that takes the configuration signals and applies them to each element depending on the network instructions.

● **Communication Module:** A basic low-power receiver (e.g. one used in Bluetooth or ZigBee) to accept control commands in a BS or a central controller.

6.2.2. Synergy with Other 6G Technologies

RIS will serve as a multiplier to other 6G technologies:

● **RIS for THz:** RIS has the capability to establish strong NLoS connections to THz signals avoiding obstacles and removing high path loss and blockage sensitivity [107], [121] THz waves can be successfully bent around corners by an RIS.

● **RIS for ISAC:** RIS may be set up to help the communication, as well as, design virtual apertures to sense, enhance the resolution and coverage of ISAC systems [87], [122].

● **RIS and FAS:** In FAS, the transmitter/receiver is reconfigured, whereas in RIS, the channel is reconfigured. They are capable of being optimized together to have unsurpassed control over the end-to-end connection [123], [124].

6.3. Joint THz-RIS Systems: A Symbiotic Relationship

The combination of THz and RIS is the inherent and strong 6G combination. The major

drawbacks of THz communications can be overcome by the RIS:

● **Coverage Extension:** With a careful placement of RIS panels on building surfaces (or indoor walls), the area of coverage of a THz base station can be substantially increased [121], [125].

● **Robustness to Blockage:** When the direct line of sight connection is blocked the RIS is capable of supplying high-quality alternative connection [121].

● **Beam Management Simplification:** The RIS can contribute to the initial beam-alignment as well as sustain connection with mobile users as it can adjust its reflection pattern [126].

A study by researchers revealed that a THz system that is assisted by an RIS is able to sustain an uninterrupted Gbps link at various moments of dynamically changing blockages, whereas a non-RIS system would suffer a complete breakdown [121].

Discussion: Table 6 summarizes the key aspects of THz and RIS technologies. The main arguments are as follows:

1. The THz communications provide a huge bandwidth to Tbps data rates yet are limited by propagation loss, blockage, and immature hardware, with solutions such as UM-MIMO and RIS allowing it to be practically implemented [104], [107].

2. RIS presents the paradigm of intelligent radio environment, which allows software-defined control of wave propagation to achieve better coverage, spectral and energy efficiency without the use of complicated RF chains [127], [128] .

3. THz and RIS synergy is essential: RIS is capable of delivering the robustness demanded by the link in the network and extended coverage of THz communication to ensure that it becomes a viable part of 6G ecosystem [105], [107], [121], [125].

Table 6. Summary of Terahertz Communications and Reconfigurable Intelligent Surfaces.

Aspect	Terahertz (THz) Communications	Reconfigurable Intelligent Surfaces (RIS)

Core Principle	Exploiting vast bandwidth (0.1-10 THz) for extreme data rates.	Software-controlled manipulation of the electromagnetic wave propagation environment.
Primary Advantage	Tbps-level data rates, ultra-high-resolution sensing.	Enhanced coverage, spectral/energy efficiency, and link robustness without power amplification.
Key Challenge	High path and absorption loss, severe blockage, immature and costly hardware. Channel estimation for a large passive surface, joint optimization with active nodes, standardization.	
Enabling Technology Ultra-Massive MIMO (UM-MIMO), novel transceiver architectures, advanced channel coding.	Metamaterials, tunable elements (PIN diodes, varactors), low-power control circuits.	
Synergistic Link	Relies on RIS for coverage extension and blockage mitigation.	Can be used to enhance any frequency band, but is particularly critical for high-frequency bands like THz.
Key Application	Wireless backhaul, kiosk downloading, intra-chip communication.	Creating virtual LoS paths, cell-edge enhancement, physical layer security, sensing augmentation.

7. The 6G Application Horizon: Digital Twins to the Metaverse

Instead of being a series of minor enhancements, the 6G core technologies of 6G-native AI, FAS, ISAC, THz and RIS are driving a range of applications that were previously inconceivable. These technologies merge forming a cyber-physical continuum to the extent that the boundaries between the digital and physical are blurred. In this section, the discussion is made on the flagship use-cases which characterize the 6G application horizon, in which the network transforms into a sensing, intelligent and immersive interaction platform [129], [130].

7.1. Networked Digital Twins

Digital Twin (DT) denotes a dynamic and virtual model of a real-life object, system, or process that is constantly updated on the physical counterpart through sensors and communication connections [131], [132]. Although DTs do exist currently, they are largely confined to small-scale industrial systems. 6G is going to make it possible to have Networked Digital Twins across a societal level in the form of a coordinated digital representation of whole cities, factories, or even the human body [133], [134].

● **Technical Enablers:** ISAC is the source of real-time and high-resolution data to

develop and revise the DT. THz and FAS provide the ultra-high-speed and dependable connectivity extensive sensor data streaming. The edge SLMs can do local inference and update models whereas larger AI models in the cloud can optimize the overall twin.

● **Use Cases:**

○ **Smart City Management:** A city-wide DT would be able to simulate real-time traffic flow, energy consumption, and emergency response and proactively optimize and manage it [135], [136].

Industrial Metaverse: Factories can simulate a DT of their complete production line, and can predictively prevent breaks, virtually commission a new one and collaborate with

experts remotely in a photorealistic virtual world [137], [138], [139].

○ **Personalized Healthcare:** A DT of a patient, constructed on a base of continuous ISAC-based vital sign measurements and medical records, predicts health events and simulations of the effects of alternative treatment plans [140], [141].

Figure 8 depicts the design of a large-scale networked digital twin, presenting the stream of data between the physical and virtual components through the 6G network.
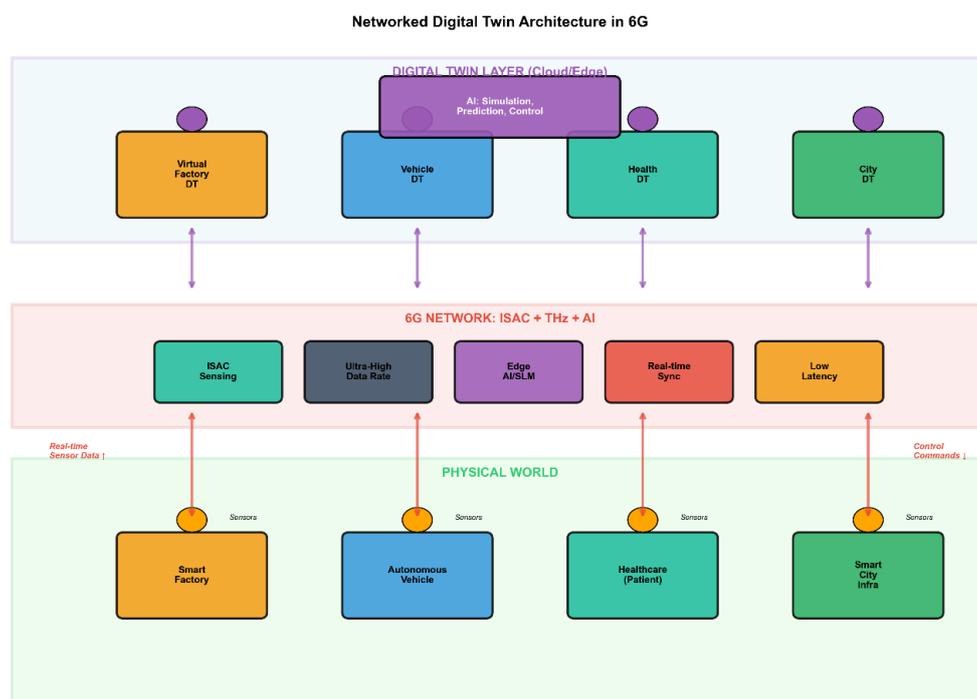

Figure 8. Architecture of a Networked Digital Twin in a 6G System.

Figure 8 shows a diagram showing physical entities (a factory, a vehicle, a human) connected via 6G ISAC and communication links to their high-fidelity digital twins in the cloud. AI models process the data for simulation, prediction, and control, which is fed back to the physical world.

7.2. The Immersive Metaverse and Holographic Telepresence

The Metaverse is expected to be a persistent, shared, and immersive virtual world that

features users communicating as avatars and connecting with each other, surpassing the current headsets of Virtual Reality (VR) that are tethered to a computer to move into untethered,

photorealistic environments supported by 6G [142], [143].

● **Technical Enablers:** THz communications are essential in delivering the huge data necessary to produce photorealistic graphics and holograms (which is estimated to be several Tbps in order to produce a full immersion [144], [145]). FAS and RIS will provide high-quality, low-latency connections to preserve the user presence and avoid motion sickness.

● ISAC is able to trace user movements and gestures in a very fine manner to have natural interaction [146], [147], [148].

- **Use Cases:**
  - **Holographic Telepresence:** Holographic Telepresence: Holograms Users can introduce life like and 3D holograms of themselves into a long distance meeting, creating a feeling of being there which is far better than any existing video conferencing [149], [150].
  - **Social and Entertainment Metaverse:** Attending a virtual concert with friends worldwide, being in the middle of the crowd and the music, or visiting virtual museums where artifacts replicas are shown in a three-dimensional form, in detail [151], [152].
  - **Collaborative Design and Engineering:** When viewing complex structures such as aircraft engine on 3D real-time, global teams are able to interactively design and immediately see the result displayed in the shared virtual environment [153], [154].

7.3. Swarm Intelligence and Autonomous Robotics

With 6G, it will be possible to coordinate large swarms of autonomous agents of drones, robots and vehicles into intelligent swarms that can coordinate to complete complex tasks [155], [156].

- **Technical Enablers:** The safety of swarm coordination is most important to the ultra-reliable low-latency communication (URLLC) in 6G, owing to the FAS-enhanced capabilities to support robust links [157]. ISAC enables every agent to feel its surroundings and communicate the feel to the swarm to form a hive mind. The swarm can be able to make decisions distributed with the help of SLMs [8], [39].
- **Use Cases:**
  - **Disaster Response:** In an autonomous way, a fleet of drones and earth robots will be able to surveille an area of disaster, identify survivors with thermal and ISAC sensors, and deliver resources, coordinate their movements in real-time [158], [159].
  - **Precision Agriculture:** There will be swarms of autonomous drones and tractors that can be used to monitor the health of crops, direct pesticide spray, and harvest crops with limited human oversight using a 6G network that spans large rural regions [160], [161].

  - **Autonomous Logistics:** Fleets of self-driving trucks and warehouse robots can coordinate to optimize supply chains, with RIS-assisted links. These will ensure continuous connectivity in complex environments like ports and distribution centers [162], [163].

7.4. Pervasive Intelligence and Ambient IoT

The 6G will experience a growth of the Ambient Internet of Things (AIoT) in which billions of cheap, battery-free sensors are infiltrated into the environment, with ambient energy collection and backscatter communication [2], [13], [164].

- **Technical Enablers:** The energy efficiency of SLMs and ultralow-power operation of advanced backscanner tags (based on the principles of BackCom) are important. These devices may be powered with RIS by point source in this manner and by ISAC through localization and reading without the tags having complex active radios [165], [166], [167].

- **Use Cases:**
  - **Smart Buildings:** Walls, furniture, and objects around us can be fitted with sensors that track temperature, occupancy, and structural well-being and allow truly responsive and energy-efficient buildings to be created [168], [169].
  - **Environmental Monitoring:** Large geographical areas can be monitored with dense networks of disposable sensors to monitor the quality of air and water, the condition of forests and the activity of wildlife [170], [171].
  - **Product Authentication and Tracking:** Each item in a supply chain has the ability to carry a battery-free tag that can track products at the item level and prevent counterfeiting between the factory and the consumer [172].

Discussion: able 7 provides a summary of the most important 6G applications and driving technologies. The key arguments are as follows:

1. **Networked Digital Twins** include ISAC, AI and high capacity connections to generate dynamic virtual models about physical systems to optimize and simulate, transforming realms in urban planning through healthcare [173], [174].
2. **The Immersive Metaverse** is based on the high data rates of THz and the stability of FAS/RIS as well as the capabilities of ISAC to provide shared virtual experiences but in real

time, seamlessly and in photorealism [175], [176].

3. **Autonomous Swarms** can be supported by the ultra-reliable and low-latency communication and distributed perception features of the 6G URLLC and ISAC features in order to support safe and efficient collaborative automation [177], [178].

4. **Pervasive Intelligence and Ambient IoT** are enabled by the convergence of low-power SLMs, advanced backscatter, and RIS, turning the environment into a smart, sensing fabric [87], [179].

Table 7. Summary of Key 6G Applications and Enabling Technologies.

Application	Core Function	Key Enabling 6G Technologies	Impact
Networked Digital Twins	Real-time virtual replication of physical systems for simulation and control.	ISAC (data acquisition), AI/SLMs (model intelligence), THz/FAS (data transport).	Proactive optimization, predictive maintenance, remote operation.
Immersive Metaverse & Holography	Persistent, shared, and photorealistic virtual worlds and telepresence.	THz (Tbps data rates), RIS/FAS (robust links), ISAC (user tracking).	Revolutionized social interaction, remote work, and entertainment.
Autonomous Swarms	Coordination of massive numbers of drones, robots, and vehicles.	URLLC (control), ISAC (perception), FAS (mobility management), SLMs (distributed AI).	Efficient disaster response, agriculture, and logistics.
Pervasive Intelligence (Ambient IoT)	Billions of battery-free, embedded sensors for ambient data collection.	Advanced Backscatter/RIS (powering), SLMs (edge intelligence), ISAC (sensing & localization).	Truly smart environments, granular monitoring, sustainable IoT.

8. Challenges and Future Research Directions

The path to 6G is not devoid of challenges, yet it will be mostly filled with radical technologies; technical, regulatory, and societal challenges will also be significant. The desire to have an integrated, smart and omnipresent network is an issue that needs to be addressed in a solution that is of a greater complexity than ever before. This section discusses the important open issues that should be tackled by the international research society and industry in order to achieve the complete potential of 6G. Moreover, it maps out the prospective research opportunities in the future that will characterize the forthcoming generation of advancements in wireless communications [2], [180].

8.1. Open Problems

8.1.1. Harmonization of a Heterogeneous Technology Stack

6G is not an isolated technology but an intricate amalgamation of unrelated technologies- AI, sensing, THz, RIS, FAS. It is a huge task to ensure that they do not work in conflict, but in synergy [181], [182].

● **Cross-Layer Optimization:** The close interaction between the physical layer (FAS, RIS), the network layer (ISAC data) and the application layer (AI models) requires the redesign of the conventional protocol stack to be radically revamped. The optimization of the cross-layer should be conducted without disruption of stability and standardization [183], [184].

● **Resource Allocation and Interference Management:** Due to co-existence of communication and sensing signals, dynamical control of RIS, the scheduling of THz beams, the resource allocation problem becomes multi-dimensional. It is a non-trivial task to manage interference between the sensing and communication functions, and among a variety of intelligent surfaces [185], [186].

● **Unified Control and Orchestration:** A centralized controller might not be scalable in managing millions of RIS elements, FAS ports and sensing tasks. An open problem of critical importance is the development of a hierarchical or distributed control plane that has the ability to coordinate this heterogeneous ecosystem in real-time [187], [188].
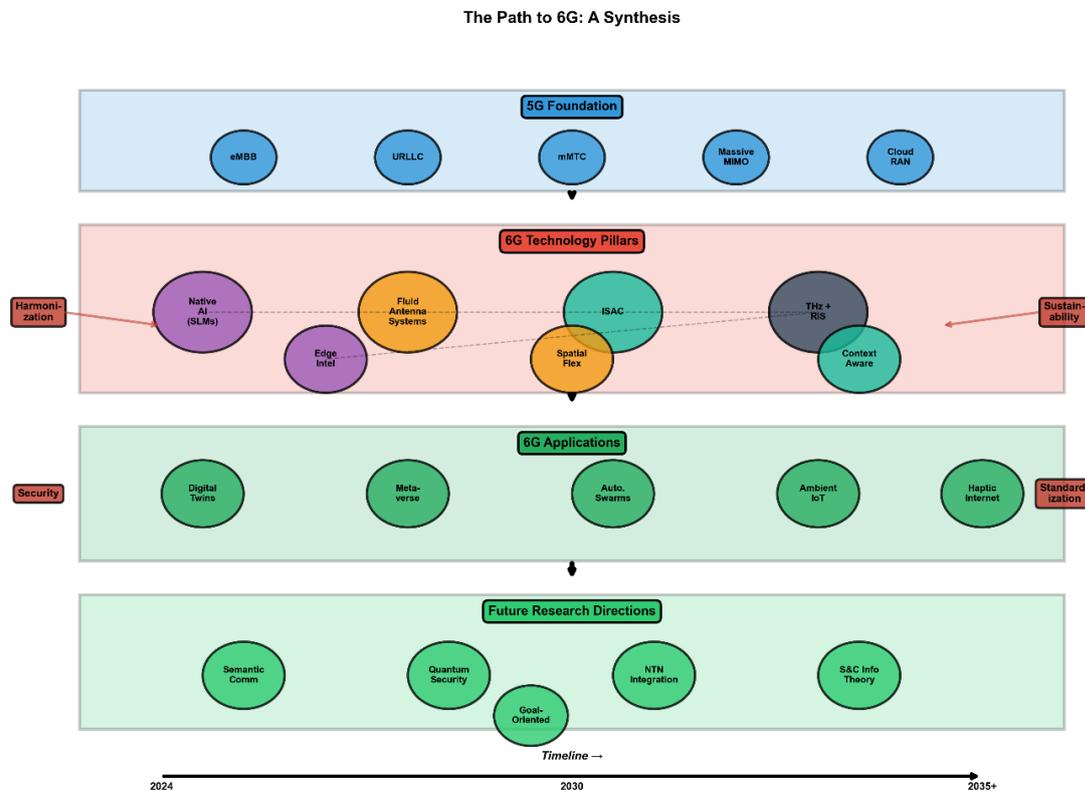

Figure 9. The Path to 6G: A Synthesis of Challenges and Innovations.

Figure 9 shows a conceptual diagram showing the journey from 5G, through the core technology pillars of 6G, which are surrounded by the key challenges (Harmonization, Sustainability, Security). Arrows point from these challenges towards the future research directions that will overcome them, leading to the ultimate 6G vision.

8.1.2. Energy Efficiency and Sustainability
The trillions of connected devices and Tbps data rates of the 6G vision may cause an unsustainable rise in energy consumption unless designed with energy efficiency as a first principle [189], [190].

● **The "Green" 6G Paradox:** Although such technologies as RIS are low-power, high-frequency circuits and dense networks might be very costly in terms of energy consumption, as ubiquitous intelligence becomes ubiquitous. Training and running the colossal numbers of SLMs should also be considered in relation to their energy footprint [191], [192], [193].

● **Hardware Efficiency:** THz transceivers and reconfigurable surfaces are currently not very energy efficient. It is important to develop new semiconductor technologies (e.g. based on GaN or graphene) and low-power control circuits in large arrays of antennas [119], [194], [195] .

● **Lifecycle Assessment:** The entire concept of sustainability, including the production of millions of sensors and metasurfaces, the energy consumption of their operation, and the ultimate e-waste must be considered as a whole. 6G should be circular [190], [196].

8.1.3. A Hyper-Connected World and Security and Privacy

The new security threats due to the 6G network are immense since the network is pervasively sensing and native intelligence.

● **The Sensing Attack Surface:** SAC makes the whole network into a giant sensor. The sensing an activity might be compromised (e.g. through reflection of communication) by the malicious actors who may be able to eavesdrop confidential information (e.g., keystrokes, conversations) or may spoof the sensing functionality to produce fake environmental data [197], [198], [199].

● **AI Model Vulnerabilities:** AI-native networks are open to adversarial attacks. A well-designed input would lead to disastrous routing or beamforming choices of an SLM, which would jeopardize network stability [49], [200].

● **Data Privacy and Sovereignty:** The fine-grained sense that is always necessary with DTs and the Metaverse poses a serious privacy challenge. This data (especially its ownership and use) is in urgent need of regulations and technological solutions (e.g., federated learning, differential privacy) [201], [202].

8.1.4. Standardization and Regulatory Frameworks

The 6G technologies have a revolutionary nature and require equally innovative regulatory and standardization strategies.

● **Spectrum for ISAC and THz:** It is also an unprecedented challenge to bodies such as the ITU and FCC to allocate and manage spectrum in two-use (sensing/communication) systems. Standards THz band operation Standards THz band operation are still in their infancy [203], [204].

● **Ethical AI Governance:** Auditing, accountability of AI, and ethical usage in the network should have standards. This involves setting performance limits and failover systems on autonomous network decisions [205], [206], [207].

● **Global Interoperability:** The interoperability of 6G networks, based on their various components, in the international context will demand unprecedented international coordination in standardizing interfaces in RIS control mechanisms, sensing data exchange mechanisms, and AI model interfaces [2], [126], [208].

8.2. Future Research Directions

8.2.1. Information-Theoretic Foundations for ISAC

It is necessary to create a new information theory that would combine the essential limits of sensing and communication. Such a region of S&C Capacity would establish the trade-off between the data rate and sensing accuracy and be used to design the future waveforms and systems [38], [209], [210].

8.2.2. Quantum-Secure Networking

Quantum computing will spell doom on existing public-key cryptography and 6G should support the post-quantum cryptography (PQC) and consider Quantum Key Distribution (QKD) to ensure long-term security of critical infrastructure and communications [211], [212] .

8.2.3. Semantic and Goal-Oriented Communications

As opposed to transmission of bits, reliable, future studies will concentrate on transmission of meaning. Semantic communication will transmit only the information that is needed to accomplish the particular task (e.g. the outcome of an inference rather than raw sensor data), which will greatly lower the latency and bandwidth demands. This is the natural extension of AI-native networks and IoT applications [213], [214], [215] .

8.2.4. Haptic and Tactile Internet

6G will also be able to touch the skin as well as the sight. The haptic feedback research on ultra-low-latency, high-reliability will facilitate remote surgery, complex remote manipulation, and highly immersive virtual experiences and demand new protocols and control theories [216], [217].

8.2.5. Non-Terrestrial Network (NTN) Integration

6G will be a single network that will encompass terrestrial (ground-based), aerial (UAVs, HAPS) and satellite networks. The seamless handovers, the issue of interference management, and routing within these highly heterogeneous and dynamic network layers require research in order to offer long, actually global coverage [218], [219] .

Discussion: Table 8 will consider the most relevant challenges and future research directions of 6G. The way forward needs an interdisciplinary approach.

1. The unification of the 6G technology stack is a systems-level challenge that extends both in hardware and software and demands novel theoretical frameworks under cross-layer design [11], [205], [218] .

2. Hardware design, network algorithms, and lifecycle management should be designed to ensure energy efficiency and sustainability, and not a secondary consideration [220], [221], [222].

3. Pervasive sensing and AI make 6G expand its attack surface, necessitating a proactive and holistic approach to security, a solution that combines cryptographic, AI-based, and regulatory solutions [10], [223].

4. The future research will also challenge the limits of the communication theory itself as it will explore the concepts of semantic, goal-based, and quantum-safe paradigm to create a network of AI that is not only faster but wiser, safer, and more user-friendly [224], [225], [226] .

Table 8. Overview of 6G Challenges and Future Research Directions.

Category	Open Challenges	Future Research Directions
Technology Harmony	Cross-layer optimization, interference management, unified orchestration.	Development of integrated system architectures, distributed control algorithms, joint S&C resource allocation theories.
Sustainability	Total energy consumption, hardware efficiency, lifecycle environmental impact.	Green AI model design, novel low-power THz/RIS hardware, circular economy design principles.
Security & Privacy	Sensing-based eavesdropping, AI model vulnerabilities, data sovereignty.	Adversarial robustness for SLMs, physical layer security for ISAC, privacy-preserving sensing, post-quantum cryptography.
Standardization	Spectrum for ISAC/THz, ethical AI governance, global interoperability.	New regulatory frameworks for dual-use spectrum, standardized APIs for RIS and AI control.
Theoretical Foundations	-	Joint S&C information theory, semantic and goal-oriented communication, quantum-secure networking.

9. Conclusion

In this broad survey, we have mapped the complex and revolutionary process of the current paradigm of 5G towards the ideal horizon of 6G wireless communications. We have started with a definition of the inherent constraints of the 5G network, including its rigid architecture, compartments of functionality, and superimposed intelligence, in the face of the staggering Key Performance Indicators (KPIs) and immersive applications of the 6G world. This examination defined the strong necessity of a sequence of paradigm changes throughout the whole network stack.

We then formulated and expounded on the main technological pillars that will support this transition. We started with the history of native artificial intelligence, as we move towards resource-efficient Small Language Models (SLMs) that can be agile and task-specific, which will be able to provide real-time, distributed intelligence in the network fabric.

Second, we explored the physical layer revolution, including the description of the shift away of the old paradigm of multiple-antennas systems and the new paradigm of Fluid antenna Systems (FAS) dynamic and reconfigurable

systems that offers unprecedented spatial diversity and efficiency.

Third, we considered the combination of communication and sensing into Integrated Sensing and Communication (ISAC), a combination that will take the network off of the data pipe and onto the active, context-responsive perceptual plane.

Fourth, we went to the extremes of spectrum and spatial control through the analysis of the enormous potential and the overwhelming challenges of Terahertz (THz) band communications and the smart radio environment enabled by Reconfigurable Intelligible Surfaces (RIS), with critical symbiosis.

It was then demonstrated that convergence of these technologies enables a new to open an application horizon, such as large scale Networked Digital Twins, truly immersive Metaverse, coordinated Autonomous Swarm, and ubiquitous fabric of Ambient IoT. Nonetheless, this positive future remains subject to the conditions of overcoming serious problems in the harmonization of the system, its sustainability in energy, its security, and its international standardization.

We have summarized by identifying the opportunities of future research, both in setting new information-theoretic foundations of ISAC and in introducing semantic communications and quantum-secure networking.

To conclude, 5G to 6G is not a simple evolution of the technology but rather a radical re-architecturing wireless networks to a distributed, intelligent and synergistic cyber-physical platform. The enablers of this new era are the technologies that are being surveyed, which are Native AI, FAS, ISAC, THz, and RIS. Although significant challenges in research still exist, the fact that the world is working collectively to overcome these challenges is a sign that one day, 6G will be used to seamlessly merge the digital and physical worlds, which will eventually transform the human interaction, industry and society itself.

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