6G System Design: Realistic Modeling, Simulation and Verification of Next Generation Wireless Systems

KEYSIGHT

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Overview

This whitepaper presents a forward-looking perspective on how Keysight's SystemVue software platform empowers the design, modeling, and verification of complex 6G systems. As 6G envisions the convergence of ultra-fast communications, integrated sensing, and native AI capabilities across diverse environments — including terrestrial, aerial, and satellite domains — SystemVue emerges as a high-fidelity RF digital twin environment. It bridges the gap between the initial design and development and physical-layer hardware by accurately modeling RF impairments, phased arrays, antenna element interactions, and system-level behaviors, all within a hardware-in-the-loop and measurement-aware workflow.

This paper explores key 6G enablers such as Integrated Sensing and Communication, Reconfigurable Intelligent Surfaces, Non-Terrestrial Networks, and AI-native networks. It illustrates how SystemVue facilitates end-to-end simulation of these technologies, enabling designers to model realistic signal propagation, evaluate advanced algorithms like neural-network-based DPD, and optimize system performance in challenging RF environments. Through these capabilities, SystemVue accelerates architectural exploration, enhances design confidence, and supports first-pass success — making it a critical enabler for researchers, system architects, and engineers working at the forefront of 6G innovation.

Introduction to 6G Systems

The next generation of wireless systems, 6G, is expected to deliver significantly higher throughput, increased capacity and coverage, and ultra-low latency compared to its predecessors. Building on the technological foundation established by 5G, 6G will introduce transformative capabilities that enable new and advanced applications, such as immersive extended reality, real-time digital twins, and autonomous systems. While 5G networks leverage a mix of sub-7 GHz and millimeter-wave frequencies, along with technologies like massive MIMO, beamforming, network slicing, and virtualization, they have not yet delivered the anticipated return on investment. Many operators have struggled to offset the substantial capital expenditures of 5G deployments, especially in terms of energy efficiency and broad coverage. 6G is being designed to address these shortcomings and meet far more demanding performance targets.

Although the development of 6G technologies is still in its early stages, several key milestones have already been defined by international standardization bodies and industry leaders. The International Telecommunication Union Radiocommunication Sector (ITU-R) has initiated the IMT-2030 vision project [1], which outlines the requirements and roadmap for 6G. Meanwhile, the 3rd Generation Partnership Project (3GPP) has begun exploratory studies on beyond-5G systems and aims to release the first formal 6G standard around 2028 [2]. In parallel, numerous countries have launched national research initiatives, funding programs, and experimental testbeds to drive innovation and accelerate the development of 6G technologies. These collective efforts are laying the groundwork for a more intelligent, resilient, and universally accessible wireless future.

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1 ITU-R IMT towards 2030 and beyond (IMT-2030) https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx

2 3GPP Rel-20 milestones and endorsed deadlines https://www.3gpp.org/specifications-technologies/releases/release-20

Technical and Economic Drivers for 6G

The evolution toward 6G is primarily fueled by the need to address emerging technological demands that surpass the capabilities of 5G networks. While 5G has introduced faster speeds and lower latency, 6G is expected to offer transformative improvements, including data rates in the terabit-per-second range, latency as low as sub-millisecond levels, and native integration of AI throughout the network. These advancements are essential to support future applications such as holographic communications, pervasive augmented and virtual reality, ultra-precise industrial automation, and real-time digital twins. Additionally, the integration of technologies like AI-driven Radio Access Networks (AI-RAN), Reconfigurable Intelligent Surfaces (RIS), Integrated Sensing and Communication (ISAC), and Non-Terrestrial Networks (NTN) are being explored to create networks that are not only faster and more reliable but also context-aware and highly adaptive.

Economically, 6G development is driven by the need for sustainable business models that provide higher value and efficiency than 5G. Despite the hype, 5G has faced economic challenges, including high infrastructure costs and a slow return on investment, especially in consumer markets. With 6G, operators and technology providers are looking to optimize capital expenditures by adopting more flexible, software-defined architectures and leveraging AI to reduce operational complexity. The introduction of digital twins and predictive analytics is expected to improve deployment accuracy and minimize testing costs, thus lowering the total cost of ownership. Moreover, 6G networks are being designed with energy efficiency and carbon footprint reduction as core metrics, aligning with global sustainability goals and reducing the economic burden of large-scale deployment.

On a broader scale, the race to develop and standardize 6G has significant geopolitical and economic implications. Countries that lead in 6G innovation will shape global standards and gain a competitive advantage in emerging digital markets. Investments in 6G are being prioritized not only by major telecom operators and equipment vendors but also by governments seeking technological sovereignty and leadership in critical infrastructure. This has led to increased funding for public-private partnerships, university research programs, and international collaborations focused on spectrum policy, advanced materials, and AI integration. The interplay of these technical and economic drivers is positioning 6G not just as the next step in wireless communication, but as a foundational pillar for the future digital economy.

5G Unfulfilled Promises

When 5G was introduced, it arrived with bold promises: ultra-fast data rates of up to 10 Gbps, ultra-low latency approaching 1 millisecond, massive Machine-Type Communications (mMTC), and the potential to transform industries such as healthcare, manufacturing, and transportation. However, many of these expectations have yet to be realized in large-scale, real-world deployments. While 5G has brought incremental improvements in speed and capacity, the widespread adoption of millimeter-wave (mmWave) technology, expected to drive the most substantial performance gains, has been hampered by its limited range, poor signal penetration, and the need for dense infrastructure. As a result, users in many regions, particularly outside dense urban areas, see only marginal benefits over 4G LTE.

Beyond the technical challenges, 5G has also struggled to meet its economic and industrial transformation goals. Key use cases like autonomous vehicles, remote robotic surgery, and smart city infrastructures have progressed more slowly than anticipated, hindered by the lack of a mature ecosystem and the delayed rollout of critical capabilities such as Ultra-Reliable Low-Latency Communication (URLLC). Network slicing, intended to provide customized connectivity for different verticals, remains in its infancy. These gaps between the initial vision and actual performance have led to skepticism across both consumer and enterprise markets. As a result, 6G is being designed with a renewed focus on setting realistic expectations, improving energy efficiency, and achieving deeper system-level integration to ensure that its potential can be fully realized.

6G Use Cases

6G is set to enable a new generation of transformative applications by combining ultra-fast data rates, ultra-low latency, and the native integration of Artificial Intelligence (AI) and sensing capabilities. One of the most impactful domains will be extended reality (XR) encompassing augmented, virtual, and mixed reality— where 6G will enable real-time holographic communication, immersive telepresence, and multi-sensory collaboration. These advancements will revolutionize key sectors such as remote work, education, healthcare, and entertainment. Another critical use case is the digital twin: a real-time, high-fidelity virtual replica of a physical system or environment. By leveraging continuous data streams, digital twins will support predictive maintenance, process optimization, and data-driven decision-making across industries including manufacturing, smart cities, and logistics.

Beyond immersive and industrial applications, 6G will play a pivotal role in enabling autonomous and mission-critical systems. This includes autonomous vehicles, drones, and industrial robots, all of which demand ultra-reliable, low-latency communication and precise environmental sensing. Non-terrestrial networks comprising satellite communications and high-altitude platforms will also become essential components of the 6G landscape, expanding high-performance connectivity to rural, remote, and underserved regions while enhancing capabilities for disaster recovery and emergency response. Additional emerging applications include smart agriculture, personalized healthcare, and secure AI-native networks, all benefiting from 6G's ability to seamlessly unify communication, computation, and intelligence in dynamic and adaptive architecture.

As these technologies are increasingly adopted throughout the 6G lifecycle, many aspects of daily life will be enhanced by ultra-high-speed, highly reliable wireless connectivity, embedded AI, and advanced sensing. Based on these core capabilities, five major categories of usage scenarios have been identified, as illustrated in Figure 1. Among them, eMBB (enhanced Mobile Broadband), URLLC (Ultra-Reliable Low-Latency Communication), and mMTC (massive Machine-Type Communications) represent evolutions and combinations of use cases originally defined in 5G. Meanwhile, sensing and AI emerge as two entirely new pillars that will thrive in the 6G era. The following section explores these categories in detail, presenting representative use cases and corresponding requirements. To meet the diverse demands of these applications and usher in a new era of connected intelligence, 6G will require significant advances in air interface design, marking a paradigm shift in wireless system architecture, as depicted in Figure 2.
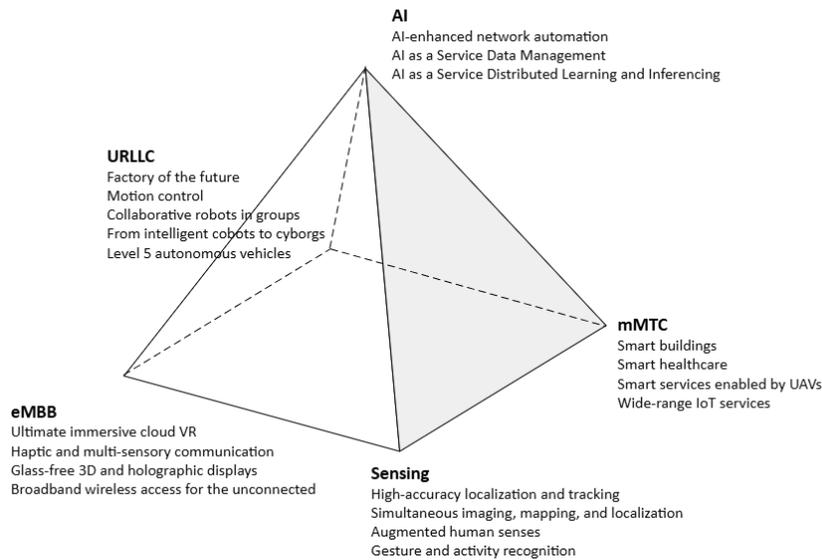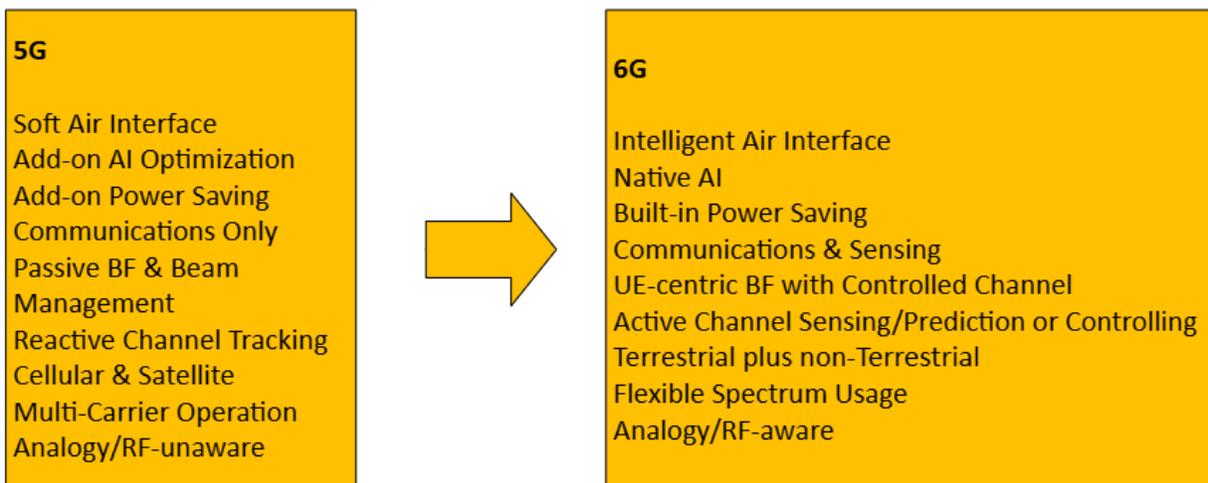

AI
AI-enhanced network automation
AI as a Service Data Management
AI as a Service Distributed Learning and Inferencing

URLLC
Factory of the future
Motion control
Collaborative robots in groups
From intelligent cobots to cyborgs
Level 5 autonomous vehicles

mMTC
Smart buildings
Smart healthcare
Smart services enabled by UAVs
Wide-range IoT services

eMBB
Ultimate immersive cloud VR
Haptic and multi-sensory communication
Glass-free 3D and holographic displays
Broadband wireless access for the unconnected

Sensing
High-accuracy localization and tracking
Simultaneous imaging, mapping, and localization
Augmented human senses
Gesture and activity recognition

Figure 1. Typical 6G use cases

5G

Soft Air Interface
Add-on AI Optimization
Add-on Power Saving
Communications Only
Passive BF & Beam Management
Reactive Channel Tracking
Cellular & Satellite
Multi-Carrier Operation
Analogy/RF-unaware

6G

Intelligent Air Interface
Native AI
Built-in Power Saving
Communications & Sensing
UE-centric BF with Controlled Channel
Active Channel Sensing/Prediction or Controlling
Terrestrial plus non-Terrestrial
Flexible Spectrum Usage
Analogy/RF-aware

Figure 2. Paradigm shift from 5G to 6G [1, 2]

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1 ITU-R IMT towards 2030 and beyond (IMT-2030) https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx
2 3GPP Rel-20 milestones and endorsed deadlines https://www.3gpp.org/specifications-technologies/releases/release-20

3GPP and ITU-R Standardization Timeline

The development and global adoption of 6G technology will be guided by two key standardization bodies: 3GPP and ITU-R. ITU-R sets the overall vision and requirements for each generation of mobile communications, while 3GPP defines the technical specifications. For 6G, ITU-R has already initiated discussions under the IMT-2030 framework, which outlines the expected use cases, performance goals, and key technology trends. A draft of the IMT-2030 requirements was published in 2023, with the finalized recommendations expected by 2025. These will serve as the baseline for technology proposals and evaluations from industry stakeholders.

Following the ITU-R timeline, 3GPP is expected to begin formal 6G specification work around Release 21, with early study items likely starting in 2025 and the first full 6G release targeted around 2028. This phased approach mirrors the development of 5G, where early releases focused on foundational features, followed by enhancements in later iterations. Commercial deployment of 6G networks is expected to begin around 2030, in line with these timelines. During this standardization process, collaboration among governments, research institutions, and industry players will be crucial to ensure global harmonization, spectrum allocation, and interoperability — laying the groundwork for a seamless and scalable 6G ecosystem.
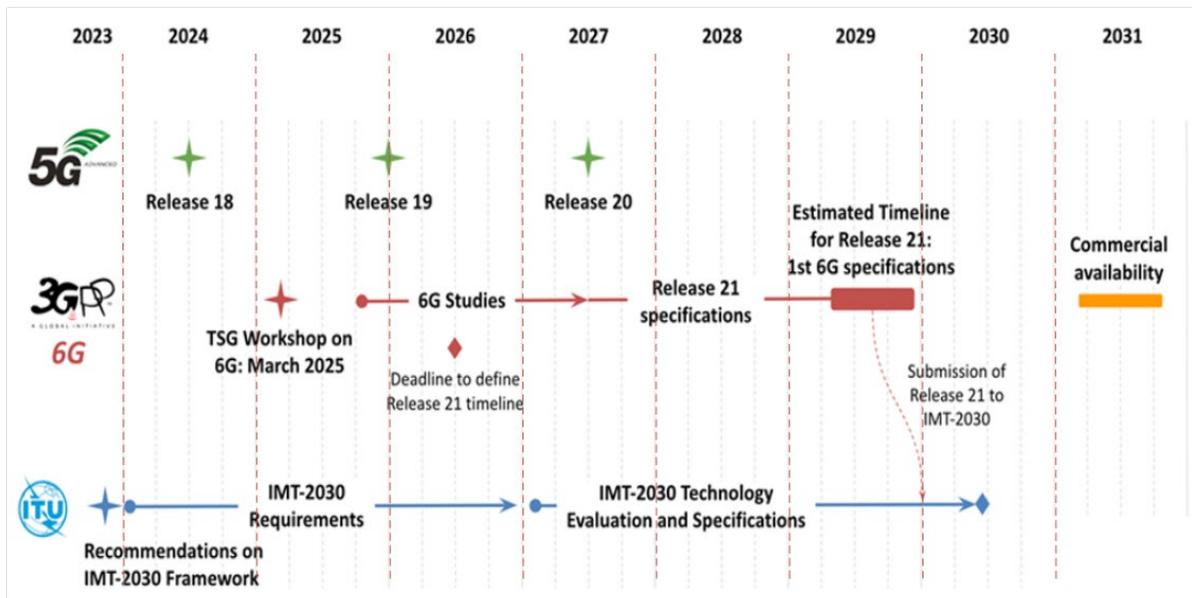

Figure 3. 6G technology development and standardization roadmap [1]

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1 3GPP Rel-20 milestones and endorsed deadlines https://www.3gpp.org/specifications-technologies/releases/release-20

Keysight 6G Vision

Keysight Technologies envisions 6G as a transformative leap in wireless communication, emphasizing sustainability, intelligence, and expansive connectivity. Building upon its 5G expertise, Keysight is actively engaged in developing technologies that will define 6G, including the utilization of sub-terahertz frequencies, AI-native network architectures, and digital twins. These innovations aim to enhance network performance, energy efficiency, and support for emerging applications like immersive extended reality and autonomous systems [1].

Collaborating with global partners, Keysight contributes to various worldwide 6G initiatives including 3GPP. By providing advanced testing and simulation tools, Keysight facilitates the development and validation of 6G technologies, ensuring readiness for the anticipated commercial rollout around 2030. Through these efforts, Keysight aims to play a pivotal role in shaping a more connected and sustainable future.

Challenges of 6G System Design

Designing 6G systems presents a host of technical challenges due to the ambitious performance targets and the integration of disruptive technologies. Unlike previous generations, 6G may operate at extremely high frequencies and wide bandwidths (e.g., sub-THz), which introduces significant difficulties in signal propagation, hardware design, and energy efficiency. These frequencies suffer from greater path loss, atmospheric absorption, and limited range, necessitating new antenna architectures like massive MIMO and intelligent surfaces to maintain connectivity. Additionally, the convergence of communication, sensing, and AI in the radio access network demands a highly complex co-design of hardware and algorithms, increasing the overall system design complexity.

Another significant challenge lies in the modeling and simulation of such heterogeneous systems. Accurate digital twin environments are needed to validate and optimize designs across multiple domains, i.e., RF, baseband, antenna, and protocol, in realistic scenarios before physical implementation. However, capturing the real-world behavior of 6G components, such as dynamic channel conditions or nonlinear RF impairments, requires high-fidelity simulation tools and vast computational resources. Furthermore, the increasing use of AI and machine learning in network functions calls for the integration of data-driven models with traditional engineering workflows, which poses both technical and methodological hurdles in system validation and reproducibility.

From an implementation standpoint, 6G design also faces regulatory, interoperability, and economic barriers. Spectrum allocation for new frequency bands must be globally coordinated to ensure device compatibility and economies of scale. Moreover, creating open and secure interfaces between hardware, software, and AI models is essential to avoid vendor lock-in and support rapid innovation. Given these factors, 6G system design is not merely an extension of 5G, it represents a paradigm shift that requires interdisciplinary collaboration, new design philosophies, and scalable development tools to manage the unprecedented complexity and ensure viable commercial deployment.

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1 Keysight 6G Communications https://www.keysight.com/us/en/learn/hubs/6g-communications.html

Setting Realistic System Requirements and Design Goals

As the vision for 6G continues to take shape, setting realistic system requirements and design goals is essential to ensure the feasibility, scalability, and long-term value of technology. While ambitious targets such as terabit-level data rates, sub-millisecond latency, and integrated AI may drive innovation, they must be grounded in practical use cases and deployment realities. Overpromising, as seen in parts of the 5G rollout, can lead to unmet expectations and slow adoption. Therefore, a balanced approach that aligns technical performance with actual market needs — such as industrial automation, immersive media, and critical communications — is key to ensuring that 6G delivers measurable benefits across sectors.

Establishing realistic design goals requires a comprehensive understanding of the trade-offs between performance, energy consumption, hardware complexity, and cost. For instance, achieving ultra-low latency or extremely high reliability may necessitate additional infrastructure or specialized hardware, which can increase capital and operational expenditures. Designers must also account for constraints in spectrum availability, device form factors, and backward compatibility with existing networks. Simulation tools, digital twins, and early prototyping can play a critical role in validating these trade-offs and identifying the optimal configuration that meets both technical and economic criteria.

Moreover, system requirements must be adaptable to regional and vertical-specific contexts. A one-size-fits-all architecture is unlikely to meet the diverse needs of applications ranging from satellite-based communication to smart manufacturing. Flexibility in system design — such as modular architecture, software-defined functionality, and support for heterogeneous network environments — will allow vendors and operators to tailor solutions to different scenarios. By defining goals that are ambitious yet achievable, and by aligning them with stakeholder expectations, the 6G ecosystem can avoid the pitfalls of past deployments and build a strong foundation for future innovation.
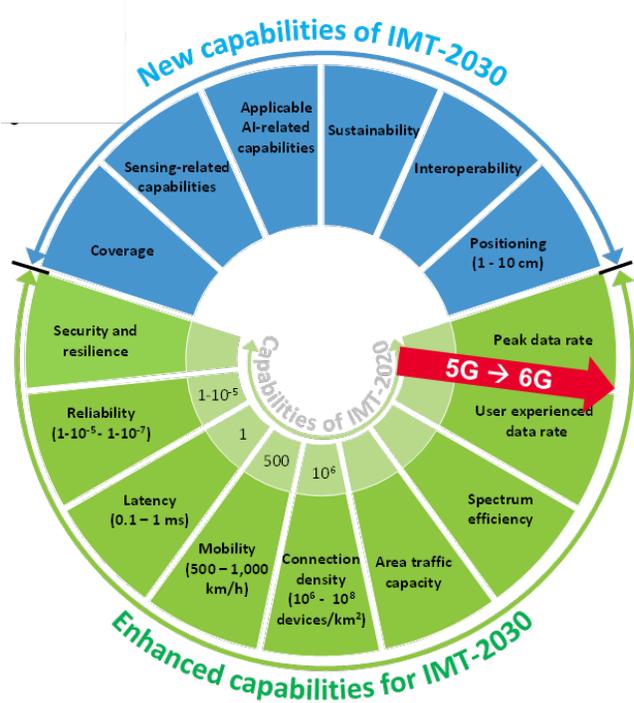
Figure 4. IMT-2030 Framework defines ITU-R vision for 6G use cases, requirements, and technologies [1].

Focus on Sustainability and Energy Efficiency

One of the central design imperatives for 6G is sustainability, with energy efficiency emerging as a critical performance metric alongside speed and latency. As networks become denser and support increasingly complex applications, their energy consumption grows dramatically, threatening both operational costs and environmental impact. Unlike previous generations, where power efficiency was often a secondary concern, 6G must prioritize low-energy architectures from the outset. This includes optimizing hardware design, using energy-aware protocols, and deploying intelligent resource management strategies that minimize waste while maximizing performance.

Advanced technologies like AI-driven network automation, dynamic beamforming, and edge computing are expected to play a vital role in improving energy efficiency. For example, AI can be used to predict traffic patterns and adjust network resources in real time, allowing systems to enter low-power modes during periods of low demand. Similarly, by processing data closer to the user, edge computing reduces the need for long-haul data transmission, saving energy and lowering latency. Additionally, innovations in materials and chip design — such as energy-efficient amplifiers and ultra-low-power transceivers — will contribute to reducing the overall energy footprint of 6G infrastructure and devices.

From a broader perspective, the 6G ecosystem must align with global climate goals and sustainability frameworks, making energy efficiency a shared responsibility across industry stakeholders, regulators, and standardization bodies. This includes adopting life-cycle assessment models that evaluate not just operational energy usage, but also the environmental costs of manufacturing, deployment, and eventual disposal. Moreover, sustainable 6G deployment strategies — including renewable-powered base stations and recyclable materials — can help reduce carbon emissions and support green digital transformation. As connectivity becomes an indispensable utility, ensuring that its growth does not come at the expense of the planet is a challenge that 6G must meet head-on.

Zero Trust and Security of 6G Systems

As 6G networks promise to interconnect everything from autonomous vehicles and industrial robots to smart cities and critical infrastructure, the stakes for security have never been higher. Traditional perimeter-based security models are no longer sufficient in an environment where devices, users, and services are highly distributed and dynamically connected. This is where the Zero Trust model becomes essential. In a Zero Trust architecture, no entity — inside or outside the network — is trusted by default. Instead, every access request is continuously authenticated, authorized, and encrypted based on context, behavior, and risk level. For 6G, implementing Zero Trust will be critical to ensure secure access across the vast and diverse ecosystem it aims to support.

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1 ITU-R IMT towards 2030 and beyond (IMT-2030) https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx

The integration of advanced technologies like AI, non-terrestrial networks, and reconfigurable intelligent surfaces introduces both new capabilities and new vulnerabilities. AI can be used to detect and respond to threats in real-time, but it can also be exploited if not properly secured. Likewise, satellite links and dynamically programmable surfaces may be susceptible to jamming, spoofing, or unauthorized reconfiguration if robust controls are not in place. Furthermore, the convergence of communications and sensing in 6G means that sensitive data such as location, biometrics, and behavior patterns will be more deeply embedded in the network — making privacy preservation a parallel concern. To address these challenges, 6G systems must incorporate end-to-end encryption, secure boot processes, trusted hardware modules, and real-time anomaly detection.

Finally, achieving strong security in 6G will require a collaborative, standards-based approach. Governments, telecom operators, equipment vendors, and cloud providers must work together to define consistent security frameworks, compliance requirements, and certification programs. As geopolitical tensions rise and cyber threats become more sophisticated, 6G security is not just a technical requirement, it's a strategic imperative. By embedding Zero Trust principles at the architectural level and treating security as a core design feature rather than an afterthought, 6G can deliver not only unprecedented connectivity but also the resilience and trustworthiness needed to support the digital society of the future.

Realistic Modeling and Simulation of 6G Systems

As 6G networks move from concept to development, realistic modeling and simulation become critical tools for designing, validating, and optimizing complex systems before physical deployment. The sheer scope of 6G — spanning sub-THz frequencies, AI-native architectures, integrated sensing and communication, and non-terrestrial networks — demands a shift from traditional modeling approaches to high-fidelity, cross-domain simulations. These simulations must account for non-linearities, interference, channel dynamics, hardware impairments, and other real-world factors that can significantly affect system performance. Without such realistic modeling, early design decisions may fail to translate into effective real-world implementations, leading to costly iterations or performance shortfalls.

Digital twins, which are virtual representations of real-world systems updated with real-time or experimental data, offer a transformative approach to 6G simulation. By mirroring the behavior of RF subsystems, antennas, and communication channels, digital twins enable developers to test 6G components and systems under diverse environmental conditions, use cases, and failure scenarios. Tools like SystemVue support this by providing near-circuit quality simulations, multi-domain co-simulation (RF, baseband, antenna), and integration with hardware-in-the-loop setups. These capabilities allow engineers to assess the performance impact of different design choices, identify bottlenecks early, and fine-tune systems for efficiency and robustness—all without the need for costly and time-consuming physical prototypes.

Furthermore, realistic modeling supports a faster and more confident path to innovation and compliance. With emerging 6G standards still evolving, simulation platforms can quickly adapt to new requirements and help evaluate technology readiness before investments are made in fabrication or field trials. They also provide a common language between different engineering teams — RF, software, AI, and system integrators — ensuring alignment and reducing the risk of integration failures. As 6G technologies become more complex and interdependent, the role of accurate, scalable, and high-fidelity simulation will be indispensable for ensuring not only technical feasibility but also time-to-market competitiveness and long-term system reliability.

Realistic Verification and Validation of the System Designs

In the context of 6G, where systems are expected to operate at unprecedented speeds, across new frequency bands, and within diverse environments, realistic Verification and Validation (V&V) of system designs become essential. Unlike previous generations, 6G systems will integrate tightly with AI, edge computing, and non-terrestrial networks, making them inherently more complex and harder to test using conventional methods. Verification ensures that each subsystem (such as RF front ends, modems, and AI algorithms) functions according to its specifications, while validation confirms that the entire system performs reliably in real-world scenarios. Achieving both requires a holistic, model-based approach that can simulate, emulate, and test across multiple domains.

One of the key enablers of realistic V&V is the use of Hardware-in-the-Loop (HIL) and Software-in-the-Loop (SIL) environments. These platforms allow engineers to test physical components and algorithms within simulated network conditions, enabling early detection of issues like interoperability failures, timing mismatches, and performance degradation. Coupling these environments with digital twins and co-simulation tools allows for system-level verification that accounts for hardware constraints, signal propagation effects, user mobility, and even security vulnerabilities. Additionally, AI-based design verification emerges as a powerful technique to detect anomalies and predict system behaviors that are difficult to observe through manual testing.

Moreover, 6G V&V processes must be repeatable, scalable, and standard-aligned to ensure deployment readiness and regulatory compliance. With global efforts to standardize 6G architectures and interfaces, verification frameworks must support automated regression testing, conformance testing, and performance benchmarking across evolving specifications. This is especially important as 6G systems move from lab-based prototypes to large-scale field deployments. By embedding realistic V&V strategies early in the design lifecycle, organizations can significantly reduce the risk of late-stage design failures, minimize time-to-market, and ensure that 6G systems are not only innovative but also robust, secure, and ready for commercial deployment.

SystemVue RF and Antenna Modeling Tool

SystemVue is a high-performance system-level design and simulation platform engineered to meet the rigorous demands of next-generation wireless technologies, including 5G, 6G, satellite, radar, and automotive systems. It brings together RF, baseband, and phased array modeling within a unified environment, supporting accurate, multi-domain simulations across both time and frequency domains. With advanced simulation engines — such as Data Flow for time-domain analysis, Spectrasys for frequency-domain analysis, Phased Array for antenna and beamforming modeling, and the WhatIF frequency planner — SystemVue enables engineers to model complex signal chains, analyze spurious emissions, and optimize system performance with near-circuit-level fidelity and exceptional speed.

SystemVue has played a pivotal role in the design, simulation, and validation of 5G wireless systems, offering an end-to-end modeling environment that spans from baseband algorithms to RF front-end components. It has allowed system architects, RF engineers, and DSP developers to simulate the full 5G signal chain under realistic conditions, including waveform generation, modulation, channel coding, beamforming, and antenna configurations. With built-in support for 5G NR standards aligned with 3GPP Releases 15 through 18, SystemVue facilitates detailed link-level analysis, Over-the-Air (OTA) simulations, and the evaluation of advanced features such as massive MIMO, carrier aggregation, and hybrid beamforming.

A key advantage of SystemVue is its seamless integration with Keysight's measurement tools, including Signal Studio and Vector Signal Analysis (VSA) software. This interoperability allows users to directly correlate simulated and measured results using consistent waveforms and performance metrics such as EVM and Adjacent Channel Power Ratio (ACPR). The platform also includes 5G-specific libraries with reference transmitter and receiver models, enabling the testing and optimization of custom algorithms for tasks like channel estimation, resource scheduling, and digital predistortion (DPD). This simulation-to-test workflow significantly accelerates development, enhances design confidence, and ensures compliance across both sub-7 GHz and FR2 5G deployments.

Prominent 6G Technologies

Among the most transformative technologies shaping 6G are AI in the Radio Access Network (AI-RAN), Integrated Sensing and Communication (ISAC), Reconfigurable Intelligent Surfaces (RIS), and Non-Terrestrial Networks (NTN). AI-RAN represents a shift toward intelligent, self-optimizing networks, where machine learning algorithms dynamically manage spectrum, power, beamforming, and handovers based on real-time conditions. Unlike static rule-based systems, AI-RAN enables predictive decision-making, improves energy efficiency, and enhances Quality of Service (QoS) in ultra-dense and heterogeneous network environments. This native integration of AI is expected to be fundamental to 6G's ability to handle the scale and complexity of future applications like immersive XR, digital twins, and autonomous mobility.

ISAC and RIS aim to fundamentally redefine the physical layer of wireless systems. ISAC enables wireless systems to perform both communication and sensing tasks using the same waveform and hardware infrastructure, opening new possibilities in environmental awareness for applications like autonomous vehicles and industrial automation. RIS, on the other hand, consists of programmable surfaces that control how electromagnetic waves propagate, enhancing signal strength, coverage, and energy efficiency without active transmission. Complementing these ground-based innovations, NTNs, which include Low-Earth Orbit (LEO) satellites, High-Altitude Platforms (HAPS), and UAVs, extend 6G connectivity to remote and underserved regions. Together, these technologies form the backbone of a highly intelligent, adaptive, and globally accessible 6G network.

Artificial Intelligence and Machine Learning (AI/ML)

Artificial Intelligence (AI) and Machine Learning (ML) are expected to be foundational components of the 6G radio access network, enabling a paradigm shift from reactive to proactive and self-optimizing networks. In 6G, AI/ML will be embedded natively within the RAN architecture to manage the growing complexity of ultra-dense, heterogeneous, and high-frequency networks. These technologies will enable real-time analysis of massive datasets generated across the network to support dynamic spectrum allocation, intelligent beamforming, and adaptive modulation schemes — all with minimal human intervention. AI-RAN will move beyond predefined rules to data-driven decision-making, increasing efficiency and reducing operational costs.

One of the most transformative impacts of AI/ML in the 6G RAN will be in resource management and network orchestration. Traditional approaches struggle to adapt to rapidly changing network conditions and diverse service requirements. AI can continuously learn from network behavior, predict user demand, and allocate resources, such as power, spectrum, and computing, more intelligently. Techniques like reinforcement learning and federated learning will also support distributed intelligence at the edge, enabling localized optimization without overloading centralized control units. This will be crucial for supporting time-sensitive applications such as autonomous vehicles, industrial automation, and tactile internet.

Furthermore, AI/ML will enhance network security, fault detection, and energy efficiency. Machine learning algorithms can detect anomalies and cyber threats by identifying deviations from normal network behavior in real time. They can also be used for predictive maintenance by flagging potential hardware failures before they occur. On the sustainability front, AI-driven energy management strategies can optimize base station activity based on traffic patterns, reducing power consumption without compromising service quality. By embedding intelligence at every layer of the 6G RAN, operators will be better equipped to deliver ultra-reliable, low-latency, and scalable services in increasingly dynamic and demanding environments.

Figure 5 illustrates an AI-enabled framework for dynamic beam and mobility management in a heterogeneous wireless network. Centralized intelligence, likely hosted in the cloud or at the core network level, collects real-time inputs from distributed base stations and user equipment, including beam measurement reports, mobility patterns, traffic distribution, and historical call data. Based on this data, the AI engine generates optimized beam policies and mobility management strategies, which are then applied to the RAN operation and possibly to non-terrestrial platforms such as drones or satellites. These policies govern how beams are formed, steered, and reassigned across multiple frequency layers to ensure continuous connectivity and optimal handover performance, even in dense urban environments. The closed-loop interaction enhances link reliability, spectral efficiency, and seamless user mobility across cells and coverage domains.
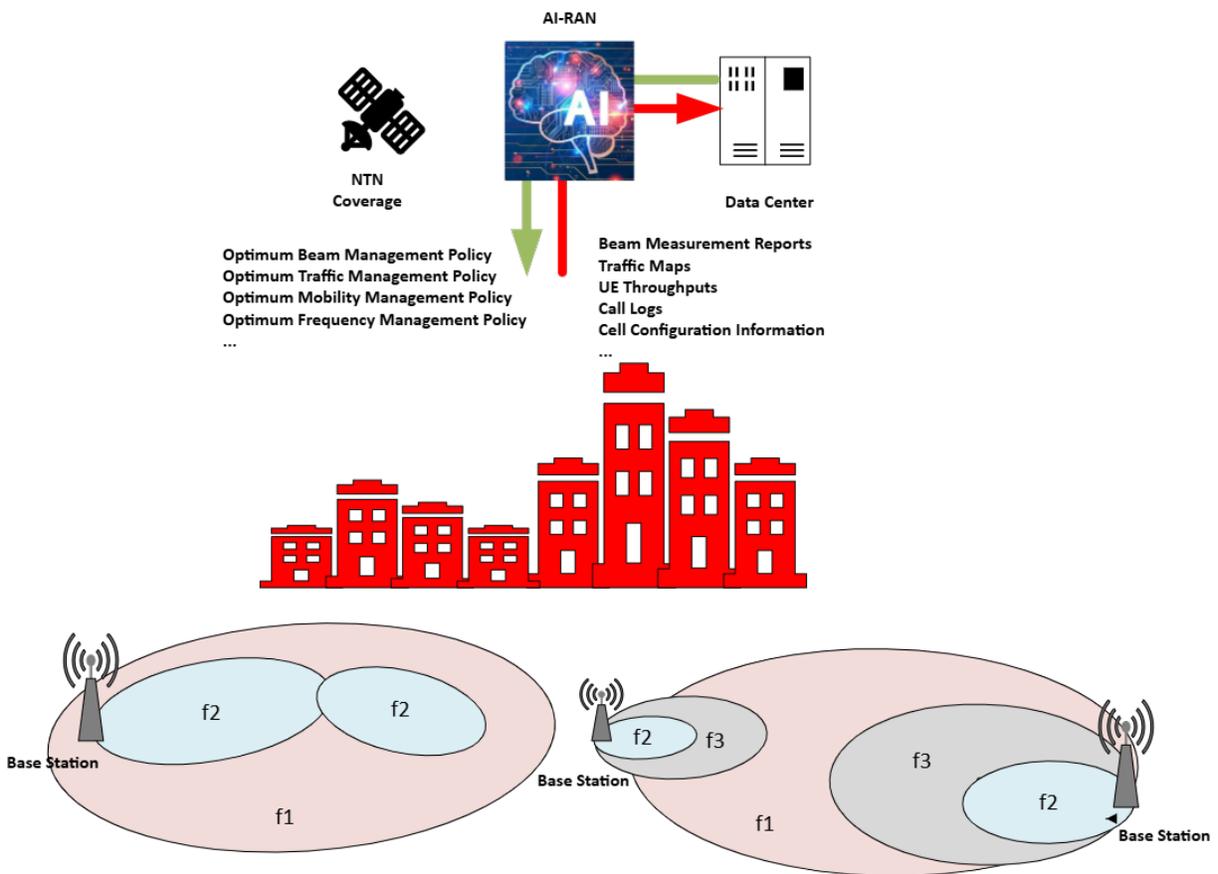

Figure 5. AI/ML adds intelligence and automation to network functions and operations.

Massive MIMO theoretically increases the number of antenna elements in the gNB and the UEs. More elements dramatically expand the CSI matrix in the spatial-frequency domain. With limited uplink resources, increasing CSI feedback overhead would pose a significant problem for 6G system designers. The CSI matrix usually consists of mostly non-zero elements at lower carrier frequencies; however, as frequency increases, it becomes increasingly sparse, containing few non-zero elements. This allows CSI feedback compression in the UE and decompression in the gNB, as shown in Figure 6. 3GPP Rel-18 study item defines a two-sided approach for CSI feedback in more detail, and we can expect more processes to benefit from similar coordination as AI/ML integration in 6G system architecture continues.

SystemVue provides a powerful environment for supporting AI-native RAN development by enabling the generation of realistic, high-fidelity training data through accurate simulation of wireless signal chains, RF impairments, propagation channels, and user mobility scenarios. Engineers can model diverse communication conditions, such as varying channel quality, beamforming configurations, or interference patterns, to create representative datasets for training machine learning models. Once trained using tools like PyTorch [1] and TensorFlow [2], these model parameters can be imported back into SystemVue to evaluate the impact of AI-based decisions (e.g., CSI feedback compression, beam management, or resource allocation) on overall system performance. SystemVue supports Open Neural Network Exchange (ONNX) and TensorFlow data formats [3]. This closed-loop workflow supports the iterative improvement of AI-RAN strategies within a unified design and simulation platform.

SystemVue provides link-level simulation of CSI feedback to enhance throughput. It saves CSI feedback information without compression for AI-based CSI feedback training. For AI channel estimation, SystemVue evaluates the performance of a 5G NR receiver model using a pre-trained neural network model, comparing it with conventional Minimum Mean-Squared Error (MMSE) channel estimation. SystemVue further generates training data for a neural network model to learn from MMSE channel estimation patterns, aiming to replace conventional MMSE channel estimation in the 5G/6G receive model.

Figure 6 depicts a machine learning–enhanced wireless communication system focused on channel state information feedback and channel estimation. It shows a typical transmitter-receiver chain, where the source block includes encoding, modulation, and beamforming. The signal propagates through a multipath channel, reaching the receiver, which performs synchronization, demultiplexing, and channel estimation. Notably, neural networks are integrated at both the receiver and feedback paths: one network is responsible for channel estimation at the receiver, while another neural network facilitates CSI feedback to the transmitter. This AI-assisted feedback loop enables adaptive beamforming at the source, improving link reliability and spectral efficiency by leveraging learned channel characteristics.

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1 PyTorch https://pytorch.org/
2 TensorFlow https://www.tensorflow.org/
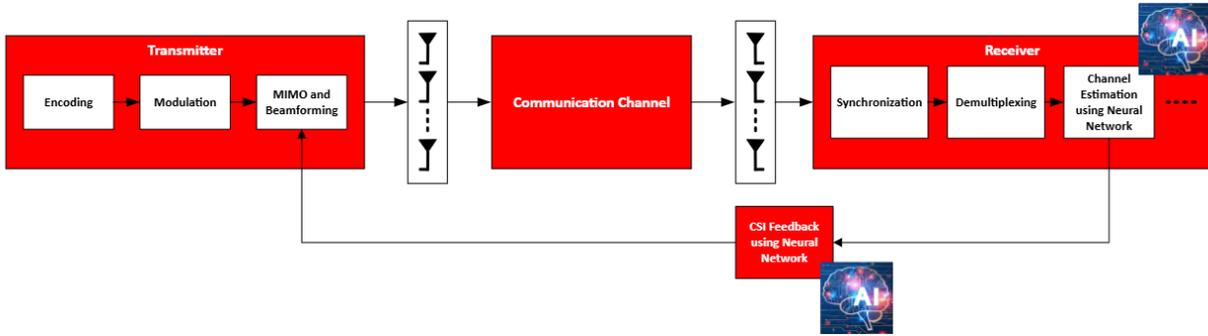3 Open Neural Network Exchange (ONNX) https://onnx.ai/

Figure 6. Example signal processing at the gNB and UE with AI/ML refining of the channel estimation and CSI feedback.

Integrated Sensing and Communication (ISAC)

Integrated Sensing and Communication (ISAC) is a core enabler in the 6G vision, unifying the traditionally separate functions of wireless communication and environmental sensing. In a 6G ISAC-enabled system, the same waveform and hardware infrastructure are used to transmit data and extract information about the surrounding environment — such as object detection, motion tracking, and spatial awareness. This fusion allows devices and networks to gain real-time context about their operating environment, which is critical for applications such as autonomous driving, industrial robotics, smart infrastructure, and extended reality. ISAC transforms communication systems from being merely data pipes into perceptive platforms capable of situational awareness [1].

From a technical perspective, ISAC introduces new challenges in waveform design, signal processing, and system-level trade-offs. Designers must balance conflicting requirements such as high-resolution sensing and low-latency data transmission within a shared frequency and hardware framework. This co-design approach requires simulation tools that can accurately model RF behavior, signal propagation, antenna configurations, and sensing performance. Traditional communication-centric modeling tools often fall short in capturing the sensing dimension, while radar tools may not support advanced communication protocols. A unified modeling platform is therefore essential for the development and validation of ISAC systems. This is where SystemVue provides a strategic advantage. SystemVue offers high-fidelity RF, baseband, and antenna system modeling within a single environment, allowing engineers to holistically design and evaluate ISAC waveforms and architectures. It supports realistic modeling of hardware impairments (e.g., non-linearities, noise, distortion, mismatches) and can simulate how these factors impact both sensing and communication performance. SystemVue also allows co-simulation of signal processing algorithms, enabling users to test detection, estimation, and classification performance under dynamic, real-world conditions. These capabilities make it an ideal platform for rapidly prototyping ISAC concepts and validating them before hardware implementation.

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1 Samir-Mohamad Omar, Towards an OFDM Radar Waveform for Detection of Far Located Targets with Relatively Low Radar Cross Sections, Digital Signal Processing Volume 114, July 2021.
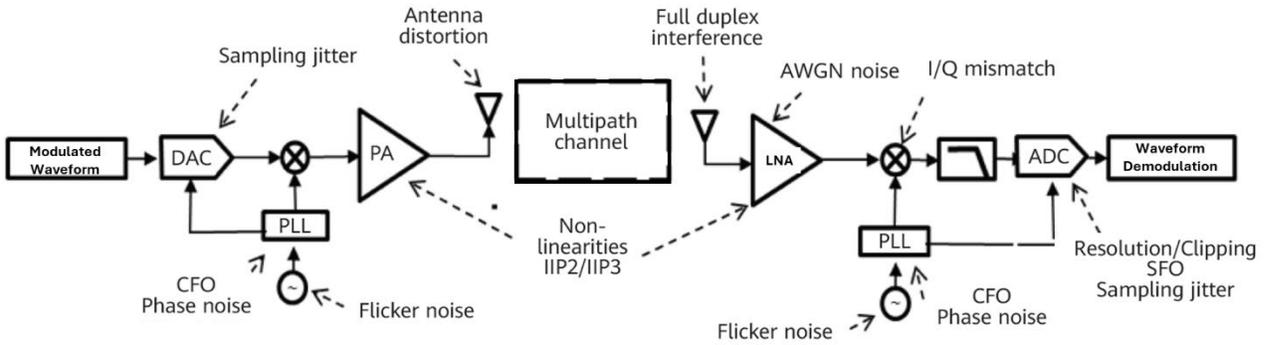
Figure 7. Modeling RF impairments in an ISAC system [1]

Figure 7 illustrates a generic transceiver signal chain encompassing both transmitter and receiver components, annotated with various RF impairments that impact end-to-end performance in ISAC systems. Key impairments such as phase noise, Carrier Frequency Offset (CFO), sampling jitter, flicker noise, antenna distortion, non-linearities (IIP2/IIP3), and I/Q mismatch are modeled across analog and digital domains. These impairments degrade system fidelity and sensing accuracy, especially in ISAC where high precision is required for both data communication and environmental perception. The diagram also reflects impairments introduced by the channel, including multipath propagation and full-duplex interference in mono-static scenario, which are critical to model when simulating realistic ISAC scenarios such as simultaneous localization and communication.

Keysight SystemVue enables realistic modeling of these impairments through its modular architecture and high-fidelity RF system simulation capabilities. It provides parameterized models for PLLs with phase noise, DAC/ADC quantization, SFO, and jitter effects, and supports advanced RF front-end modeling including non-linearities and distortion analysis for Power Amplifiers (PAs) and Low-Noise Amplifiers (LNAs). In the ISAC context, SystemVue allows joint waveform generation and impairment modeling to assess how RF non-idealities affect both communication throughput and sensing resolution. This is particularly valuable when designing RF-aware ISAC algorithms, beamforming strategies, and verifying cross-layer trade-offs. With support for co-simulation and hardware-in-the-loop validation, SystemVue becomes a comprehensive platform for developing and testing ISAC systems under real-world impairment conditions. Figure 8 depicts an example of an ISAC system where 5G NR waveforms are reused to perform both communication and sensing functions. In this example, the 5G NR OFDM waveform is post-processed to extract relative range, Doppler, direction information of two hypothetical targets in the environment.

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1 Samir-Mohamad Omar, Towards an OFDM Radar Waveform for Detection of Far Located Targets with Relatively Low Radar Cross Sections, Digital Signal Processing Volume 114, July 2021.
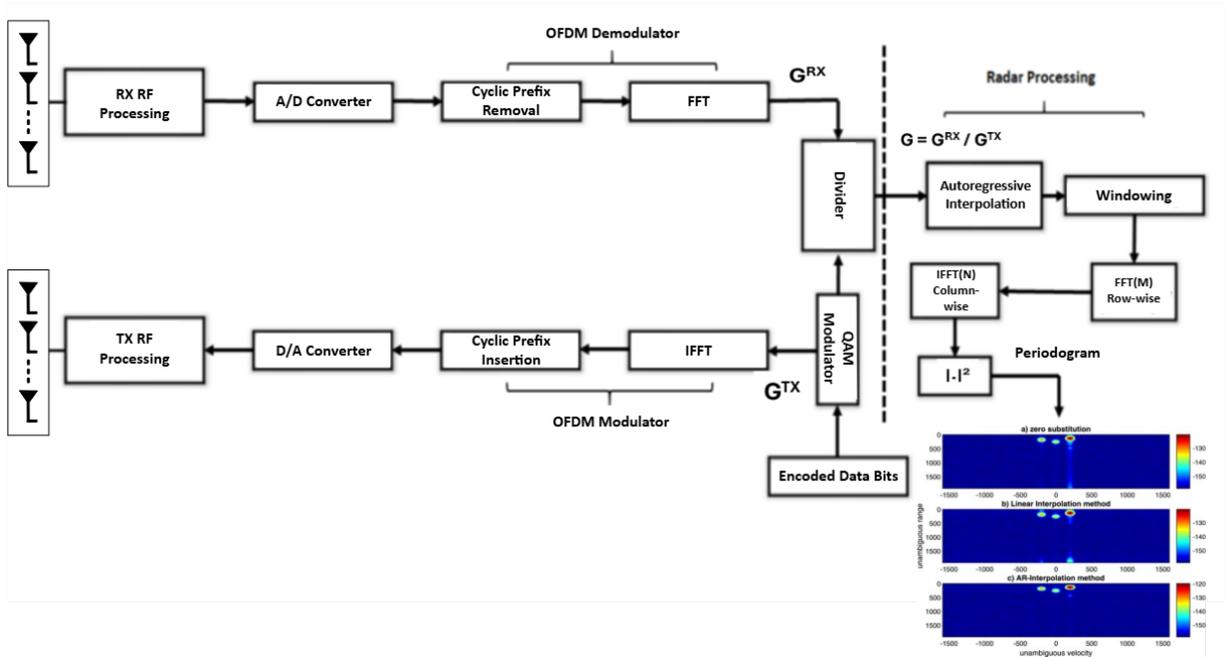
Figure 8. Example of sensing functionality by reusing 5G NR waveform [1]

SystemVue can also be integrated with Keysight's hardware-in-the-loop testbeds and instruments, enabling seamless transition from simulation to over-the-air testing. This workflow is particularly valuable for ISAC, where field performance can be highly sensitive to environmental factors and hardware limitations. By offering both the accuracy of digital twin simulation and the practicality of physical testing, SystemVue empowers researchers and engineers to innovate with confidence, reduce development cycles, and accelerate the commercialization of ISAC-enabled 6G technologies. As sensing and communication converge in the 6G era, tools like SystemVue will be indispensable for realizing robust, scalable, and intelligent systems.

1 Samir-Mohamad Omar, Towards an OFDM Radar Waveform for Detection of Far Located Targets with Relatively Low Radar Cross Sections, Digital Signal Processing Volume 114, July 2021.

Reconfigurable Intelligent Surfaces (RIS)

Reconfigurable Intelligent Surfaces (RIS) are poised to be one of the most innovative technologies in 6G, fundamentally transforming how wireless signals are propagated in a controlled manner. RIS are typically flat, programmable surfaces composed of numerous passive or semi-passive elements that can dynamically adjust their electromagnetic response to manipulate incident radio waves. By intelligently reflecting, focusing, or scattering signals, RIS can overcome challenges such as Non-Line-of-Sight (NLOS) propagation, signal blockages, and coverage holes. This allows networks to extend range, enhance throughput, and improve energy efficiency without consuming significant power or bandwidth [1].

The deployment of RIS introduces a paradigm shift from traditional infrastructure-dependent wireless design to programmable wireless environments. However, modeling and optimizing RIS-assisted systems is highly complex due to the interplay between surface design, reflection algorithms, channel conditions, and the overall communication system. Key performance parameters such as beamforming gain, reflection phase control, element layout, and interaction with multiple users and mobility must be thoroughly evaluated during the design phase. Accurate simulation is essential to predict how RIS will behave in real-world scenarios, especially at higher 6G frequencies such as sub-THz, where signal behavior becomes more sensitive to environmental and material effects.

SystemVue offers a comprehensive simulation environment that addresses these challenges by enabling realistic modeling of RIS-enabled wireless systems. Engineers can design and simulate RIS architecture by representing their phase-shifting behavior, control schemes, and impact on RF signal propagation. SystemVue's support for custom array configurations and signal chain modeling allows users to simulate how RIS interacts with transmitters, receivers, and the channel. Additionally, SystemVue can model impairments such as quantization error, reflection efficiency loss, and non-ideal switching—providing a deeper understanding of RIS performance under practical constraints.

Furthermore, SystemVue supports multi-domain and co-simulation capabilities, allowing RIS to be modeled as part of a larger system that includes baseband algorithms, RF impairments, and antenna array behavior. Integration with Keysight's electromagnetic simulation tools (like EMPro or RFPro) and OTA test systems enables a seamless transition from simulation to physical testing. This end-to-end modeling approach helps researchers optimize RIS placement, beam control strategies, and system-level interactions before committing to costly prototyping. As RIS becomes integral to 6G's vision of intelligent, programmable wireless environments, Keysight SystemVue provides the tools necessary to model, test, and validate these systems with high fidelity and confidence.

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1 Georgios C. Trichopoulos et al., Design and Evaluation of Reconfigurable Intelligent Surfaces in Real-World Environment, IEEE Open Journal of the Communications Society Vol 3 2022.
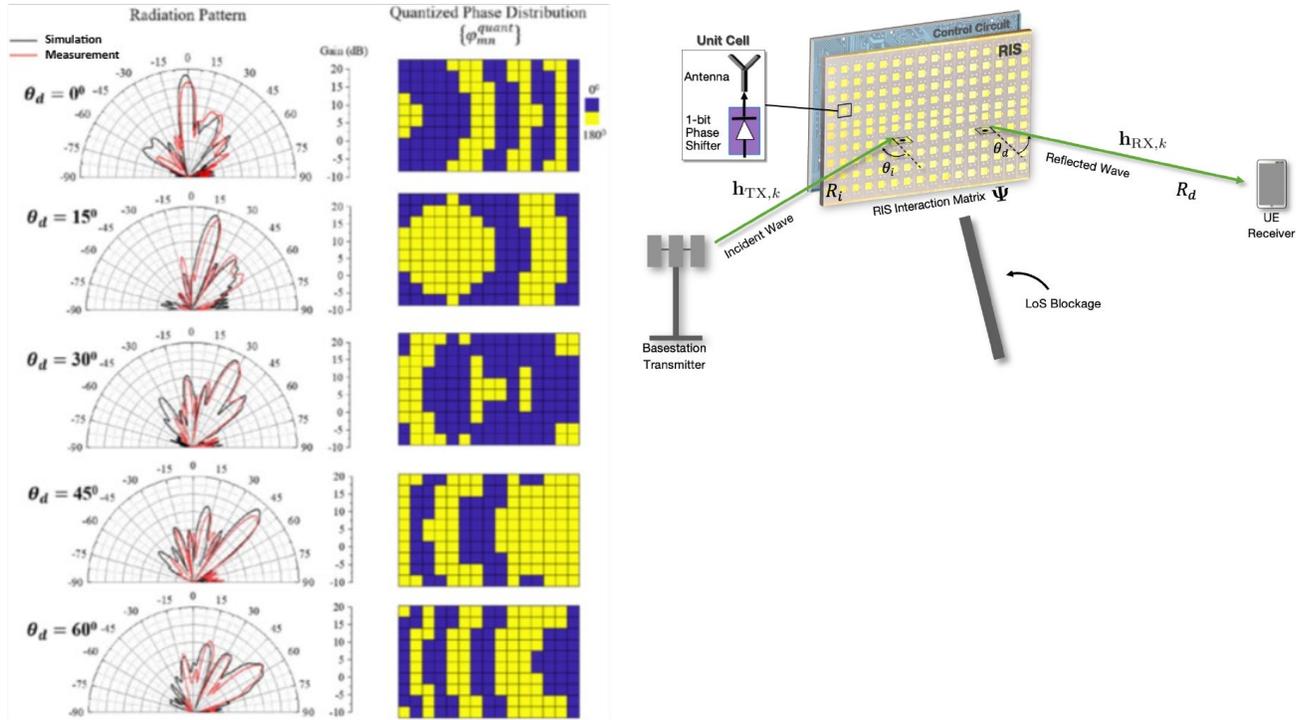
Figure 9. Characterization of the RIS beamforming for various reflection angles θ_d at 5.8 GHz showing comparison between computed and measured radiation patterns using 1-bit phase shift quantization [1].

Figure 9 presents measured and simulated radiation patterns of a reconfigurable intelligent surface at various reflection angles $0 \leq \theta_d \leq 60°$ along with their corresponding 1-bit quantized phase distributions. The left column compares simulation (black) with physical measurements (red), demonstrating directional beam steering through discrete phase control. The right column shows the 1-bit phase quantization pattern (values of 0° and 180°), applied across the RIS elements to steer the beam. These visualizations highlight the importance of accurately modeling antenna element phase, element spacing, and angular response to understand the spatial behavior and control capabilities of RIS.

SystemVue's phased array modeling environment is well-suited for RIS design and operation analysis. It enables the creation of custom planar array topologies with quantized phase control and supports element-level modeling for realistic hardware constraints like mutual coupling, element radiation patterns, and phase quantization. For RIS applications, SystemVue allows simulation of beam steering accuracy, side lobe levels, and gain performance across varying incident angles, similar to the plots shown in Figure 9. Designers can evaluate the effects of coarse phase resolution and reflection element impairments, perform joint optimization with baseband/RF system parameters, and co-simulate RIS behavior within full wireless system-level scenarios, such as downlink beamforming or sensing-assisted links. This empowers researchers to assess trade-offs between design complexity, control resolution, and RIS performance in practical 6G scenarios.

1 Georgios C. Trichopoulos et al., Design and Evaluation of Reconfigurable Intelligent Surfaces in Real-World Environment, IEEE Open Journal of the Communications Society Vol 3 2022.

Integration of Terrestrial and Non-Terrestrial Networks

The integration of Terrestrial and Non-Terrestrial Networks (NTNs) represents a key architectural advancement initiated in 5G and further expanded in 6G to enable truly global, seamless connectivity. NTNs encompass communication via satellites (LEO, MEO, GEO), High-Altitude Platforms (HAPS), drones, and airborne base stations, complementing terrestrial cellular infrastructure. This hybrid architecture is specifically designed to extend reliable coverage to remote, rural, maritime, and disaster-affected regions where traditional ground-based networks are either infeasible or unavailable. By unifying terrestrial and non-terrestrial layers, 6G aims to support persistent broadband access, global IoT deployment, aviation and maritime communications, and robust connectivity in emergency scenarios. Figure 10 highlights key NTN scenarios, including transparent and regenerative satellite payloads, as well as direct UE-to-UE links via satellite relays.

However, the integration of NTNs introduces unique system-level design challenges. These include large and variable propagation delays, significant Doppler shifts due to satellite motion, intermittent link availability, and atmospheric impairments at high altitudes. Seamless handovers between terrestrial and satellite domains, cross-layer resource allocation, and the interoperability of diverse platforms further complicate network orchestration. Additionally, NTN-specific channel models, antenna dynamics, and mobility behavior differ substantially from their terrestrial counterparts, requiring high-fidelity modeling and simulation for effective design and validation. Keysight's SystemVue addresses these complexities by offering a comprehensive simulation environment tailored for NTN system development. It supports modeling of satellite payloads, ground terminals, and gateways under realistic propagation conditions, including Doppler shift, delay spread, ionospheric/tropospheric scintillation, and polarization loss. SystemVue also enables small- and large-scale fading simulations, RF impairment modeling (e.g., PA nonlinearity, I/Q imbalance, intermodulation), and phased-array antenna design for LEO and HAPS platforms. With scenario-specific customization capabilities, engineers can evaluate the impact of beam management, mobility patterns, and satellite handovers — accelerating robust NTN-6G system design and deployment.
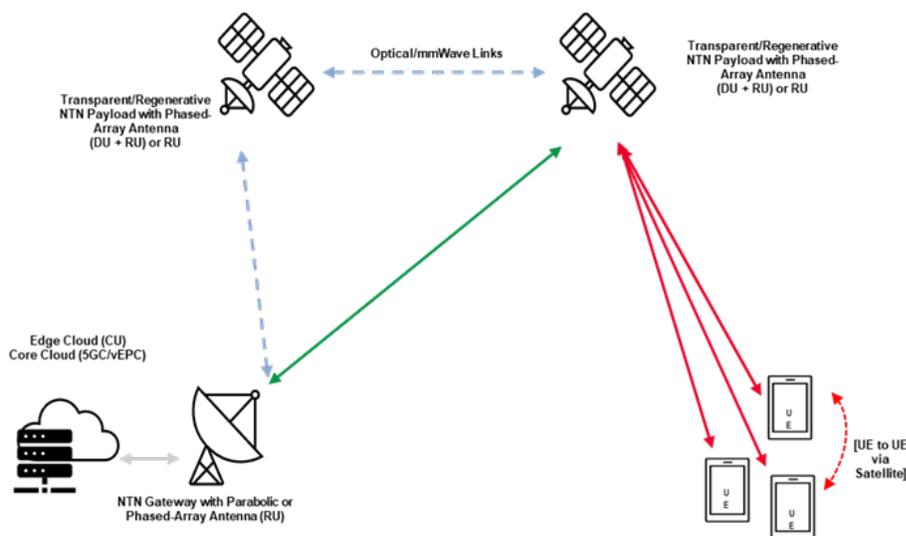

Figure 10. NTN uses LEO/GEO satellites to extend TN coverage and services

Figure 11 illustrates an example of the comprehensive NTN modeling capabilities of SystemVue including both transparent and regenerative payload scenarios. SystemVue enables accurate modeling of gateway (GW), satellite (SAT), and User Equipment (UE) RF chains, incorporating real-world impairments such as phase noise, nonlinearity of RF components, and Doppler effects. The figure emphasizes end-to-end system fidelity, showing how signals are processed through the entire system comprising gateway, satellite, and the UE. The modeling includes waveform degradation due to channel impairments, time delays, Doppler shifts, and frequency conversions, capturing the dynamic link variations in LEO satellite systems. In addition, SystemVue supports array modeling for satellite, payload, and UE antennas, enabling designers to evaluate link budgets and spatial performance with high accuracy. Integrated features such as 3D satellite trajectory visualization, nonlinear Power Amplifier (PA) modeling with and without digital predistortion (DPD), and Error Vector Magnitude (EVM) analysis provide critical insights into system behavior and optimization strategies. These capabilities allow engineers to simulate real-world operating conditions, assess link robustness, and validate system performance before hardware deployment. With SystemVue, engineers can develop, test, and validate NTN system designs that meet the stringent requirements of 5G/6G connectivity, ensuring both communication reliability and scalability across diverse satellite topologies.
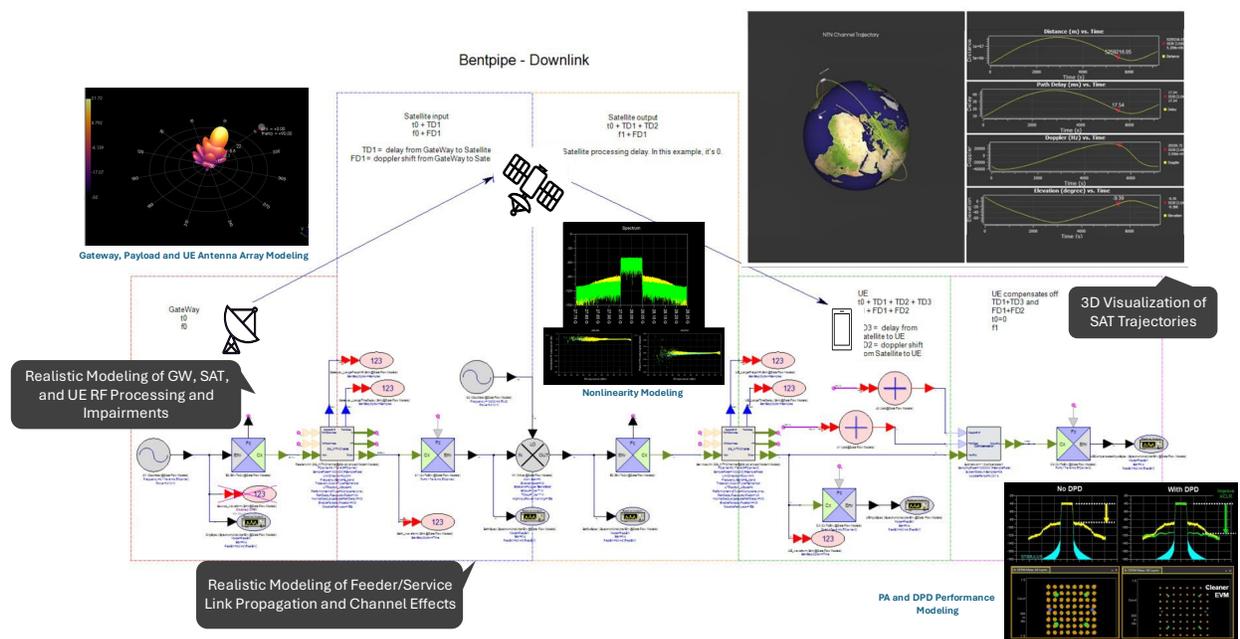

Figure 11. Example illustration of NTN link modeling using SystemVue

New Spectrum

The emergence of 6G is expected to introduce a new frequency range known as FR3, covering the spectrum between 7.125 GHz and 24.25 GHz. Positioned between FR1 (sub-7 GHz) and FR2 (24–71 GHz) used in 5G, FR3 provides a critical balance between propagation and capacity. It offers higher bandwidth than FR1 while preserving better coverage and penetration characteristics compared to FR2 and sub-THz bands. This makes FR3 particularly attractive for 6G applications such as ultra-reliable low-latency communication, extended reality, and integrated sensing and communication, where both data throughput and reliability are essential.

Despite its promise, harnessing FR3 presents several technical challenges. These include increased signal attenuation, susceptibility to interference, and the demand for advanced antenna and RF front-end designs capable of operating efficiently across wide bandwidths. Supporting higher data rates with stringent linearity requirements will necessitate innovations in beamforming, new radio architectures, and efficient channel modeling. Regulatory compliance and international spectrum harmonization will also be crucial to enable global interoperability and cost-effective deployment.

Keysight SystemVue provides a comprehensive solution for navigating these design complexities. With its high-fidelity modeling and simulation environment, SystemVue enables detailed analysis of RF signal propagation in FR3 bands, accounting for factors such as path loss, interference, and hardware impairments. Its robust support for phased arrays and multi-antenna systems makes it an ideal tool for evaluating beamforming and spatial filtering techniques critical for maintaining signal integrity in FR3 environments. SystemVue also supports waveform generation, spectrum aggregation, and coexistence studies, helping designers assess performance trade-offs early in development.

Moreover, SystemVue enables full-system simulation from baseband to RF, supporting co-design and validation of transceivers, amplifiers, and antennas optimized for FR3. Seamless integration with Keysight's measurement instruments and electromagnetic (EM) simulation tools further enhances its utility for prototyping and pre-silicon verification. This is especially valuable in early 6G research phases, where empirical data is scarce and prototyping costs are high. By providing an end-to-end modeling workflow, SystemVue accelerates innovation, reduces risk, and ensures readiness for next-generation wireless systems leveraging the FR3 spectrum.
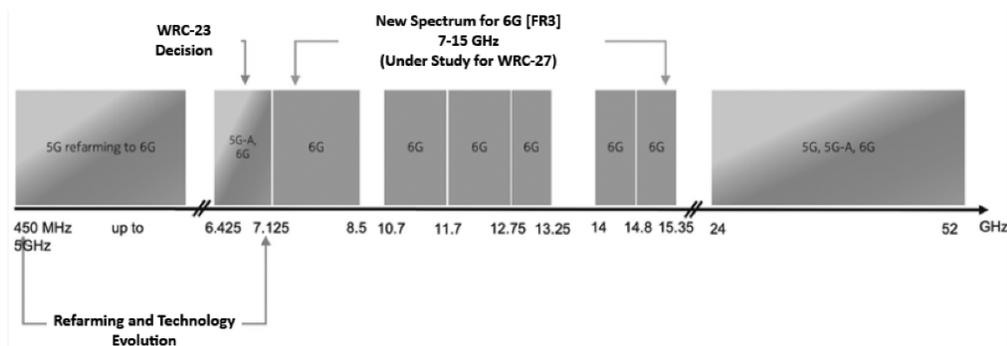

Figure 12. FR3 spectrum in 6G [1]

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1 ITU-R IMT towards 2030 and beyond (IMT-2030) https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx

New RF and Antenna Technologies

The evolution toward 6G is accelerating the development of advanced RF and antenna technologies to meet the demands of ultra-high data rates, sub-THz frequency operation, and integrated sensing and communication. Central to these innovations are novel transistor and amplifier architectures designed to operate at extreme frequencies and wide bandwidths. Emerging semiconductor technologies such as InP HEMTs, GaN-on-SiC, and CMOS-SOI enable efficient amplification at frequencies approaching 100 GHz and beyond. These materials offer high breakdown voltages and superior noise performance, making them well-suited for next-generation Power Amplifiers (PAs) and Low-Noise Amplifiers (LNAs). Architectures such as distributed amplifiers, Doherty designs, and digitally controlled beamforming PAs are being revisited and optimized to improve efficiency, linearity, and scalability in dense antenna array environments.

Simultaneously, advancements in semiconductor scaling — such as 22 nm FD-SOI, 16 nm FinFET, and smaller nodes — are enabling tighter integration of RF frontends with digital and mixed-signal components. These technologies support compact, low-power RF transceiver designs, facilitating the realization of massive MIMO and reconfigurable intelligent surfaces in smaller form factors. Approaches like Antenna-in-Package (AiP) and System-on-Chip (SoC) integration are gaining momentum, offering benefits such as reduced interconnect losses, improved impedance matching, and enhanced beamforming agility — critical for 6G applications like ultra-reliable low-latency communication and holographic streaming. Figure 13 illustrates the mapping of 6G RF front-end components to the appropriate process technologies needed to implement such advanced radio architectures.

While ultra-scaled CMOS remains suitable for digital signal processing and mixed-signal functions, RF CMOS — including SOI CMOS — offers integration advantages for components like upconverters and downconverters. However, their efficiency and power-handling capabilities diminish significantly above 140 GHz. As a result, III-V semiconductor technologies such as InP, GaN, and GaAs are considered essential for high-efficiency, high-power amplification at sub-THz frequencies. That said, recent advancements in SiGe BiCMOS have demonstrated power levels exceeding 8 dBm in the 220–250 GHz range — achieved without the use of power-combining techniques — highlighting its potential as a competitive platform for 6G RF front-end development.
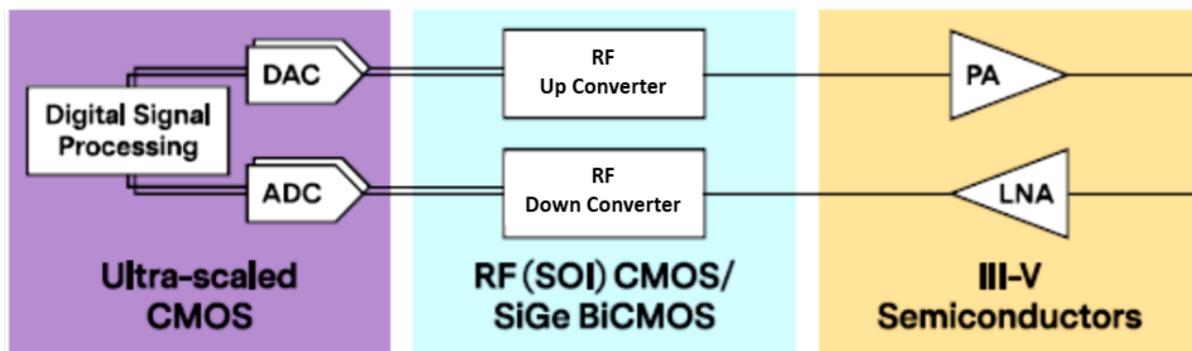

Figure 13. Semiconductor technology mapping to architecture for mmWave/sub-THz bands

A modern wireless communication system comprises both analog and digital baseband circuits interfacing with the RF front-end. The digital components continue to benefit from ongoing CMOS scaling, driven by the increasing demand for high-volume, high-performance radio chips. This evolution has progressed from traditional planar bulk CMOS to FinFET architecture and is now advancing toward next-generation 5 nm Gate-All-Around (GAA) and nanosheet transistors, which offer improved integration, performance, and power efficiency. To maintain the pace of miniaturization, scaling boosters such as super vias and buried power rails are being deployed — although these innovations increasingly contend with challenges in lithography and electrical design complexity.

Crucial analog blocks, especially data converters, are co-integrated with digital logic in these advanced nodes. Among them, Analog-to-Digital Converters (ADCs) are particularly critical in receiver chains, as they define the signal fidelity when transitioning from the RF to digital domain. Meanwhile, the rise of massive MIMO, large antenna arrays, and reconfigurable intelligent surfaces in 6G systems necessitates a shift in design methodology. Traditional electromagnetic and circuit design workflows are being enhanced with AI/ML-driven optimization, digital twin technology, and hybrid co-simulation approaches that combine circuit, system, and channel-level modeling. These approaches support co-design of physical-layer hardware and signal processing algorithms — such as beamforming and precoding — while accounting for hardware non-idealities like non-linearities, phase noise, and mutual coupling. Platforms such as Keysight SystemVue, integrated with EM simulators and measured hardware data, are becoming indispensable to ensure design convergence, accuracy, and robustness. As 6G targets dynamic, multi-user, and multi-band environments, these methodologies are essential for realizing scalable, adaptive, and energy-efficient RF and antenna systems.
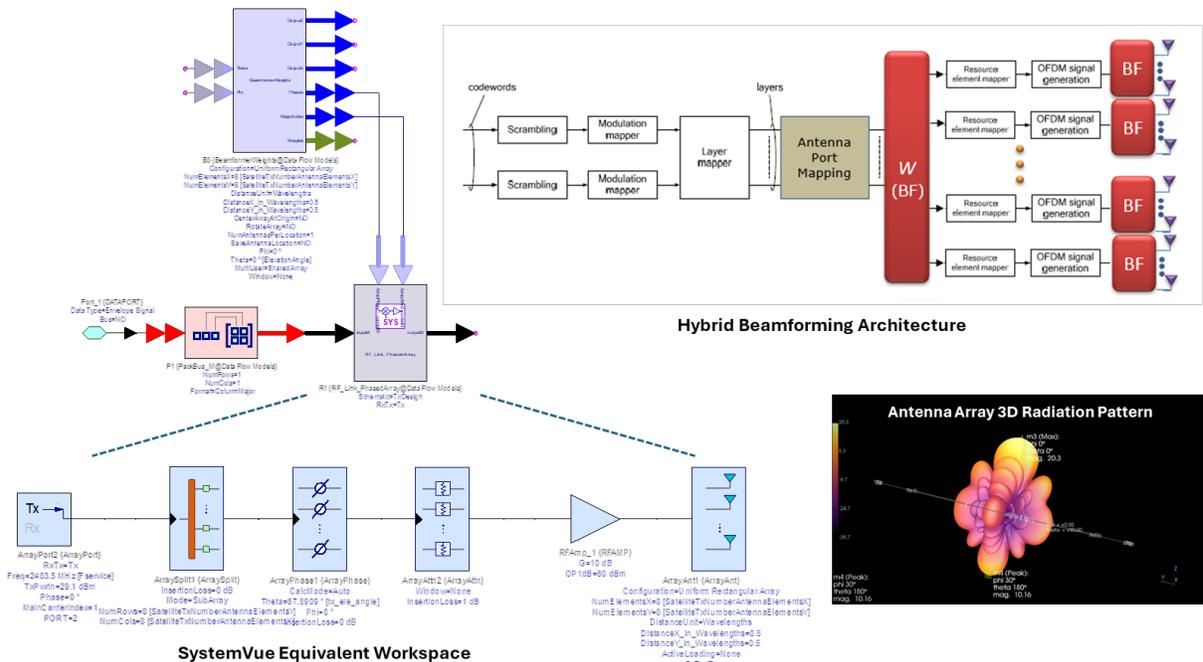

Figure 14. Using SystemVue to model massive MIMO RF and antenna systems

SystemVue plays a critical role in accelerating the development of advanced RF and antenna technologies for 6G by offering a unified simulation environment that seamlessly bridges circuit-level accuracy with system-level validation. It supports high-fidelity modeling of next-generation transistor and amplifier architectures — including GaN, InP, and advanced CMOS nodes — by integrating with circuit simulators such as ADS and electromagnetic (EM) tools like RFPro. For complex antenna systems and Reconfigurable Intelligent Surfaces (RIS), SystemVue provides array-aware system modeling, beamforming algorithm integration, phase/gain quantization, and coupling analysis. Its capabilities extend to digital predistortion (DPD), phased-array calibration, and AI-assisted optimization, enabling co-development of RF front-ends and control logic tailored for 6G environments. By combining measured hardware data, EM models, and real-time signal processing, SystemVue serves as an RF digital twin — delivering scalable, accurate, and efficient workflows essential for the design and validation of next-generation RF systems.

The phased array analysis engine in SystemVue — built on Spectrasys engine — paired with dedicated RF phased array models, enables the streamlined simulation of large-scale phased array architectures. Despite the complexity of systems that may include hundreds or thousands of components and signal paths, SystemVue's smart modeling framework allows users to construct the entire array using a simplified single-chain representation. During simulation, models automatically scale to reflect the actual number of paths based on splitter/combiner stages, eliminating the need for manual duplication and reducing the risk of design errors. This abstraction dramatically simplifies system design, making even massive arrays manageable and efficient to model. The platform also includes a robust set of predefined performance metrics and 3D beam pattern visualization tools, giving engineers deep insight into system behavior and enabling effective optimization. By simplifying representation and accelerating performance evaluation, SystemVue dramatically enhances the design cycle for cutting-edge phased array systems in 6G.

Full-Duplex Systems

Full duplex and Sub-Band Full Duplex (SBFD) communication schemes are gaining traction in 6G research as potential enablers of doubling spectral efficiency and improved latency performance. Full duplex allows simultaneous transmission and reception on the same frequency band, overcoming an inherent constraint in conventional wireless systems. However, a significant challenge lies in Self-Interference Cancellation (SIC), which must suppress the transmitted signal's leakage by over 100 dB to recover the desired received signal. SBFD offers a practical compromise by enabling simultaneous transmission and reception over non-overlapping sub-bands within a broader frequency channel, reducing the stringency of SIC while still achieving spectral reuse. These technologies are particularly relevant for ultra-dense deployments, integrated sensing and communication, and low-latency applications where bidirectional communication is time-critical.

Figure 15 illustrates the architecture and operation of an SBFD Remote Radio Unit (RRU), which is designed to mitigate self-interference in full-duplex 5G/6G systems. The upper portion of the diagram depicts the SBFD RRU enabling simultaneous uplink and downlink transmissions within the same frequency band by isolating them into different subbands. Key components include subband analog filters and digital self-interference cancellation mechanisms that suppress transmitted signal leakage picked up during reception. The downlink signal is transmitted through a Digital-to-Analog Converter (DAC), Power Amplifier (PA), and filter, while the uplink signal is received via a Low-Noise Amplifier (LNA), analog filter, and Analog-to-Digital Converter (ADC), with digital SIC applied post-conversion. The lower part of the figure

shows a flexible frame structure supporting dynamic time-division of slots into downlink (D), uplink (U), and flexible (F) slots. Subband 1 is allocated for downlink and Subband 2 for uplink, allowing simultaneous bidirectional communication while maintaining frequency and temporal isolation. This flexible configuration enhances spectral efficiency and adaptability in real-time traffic scenarios.
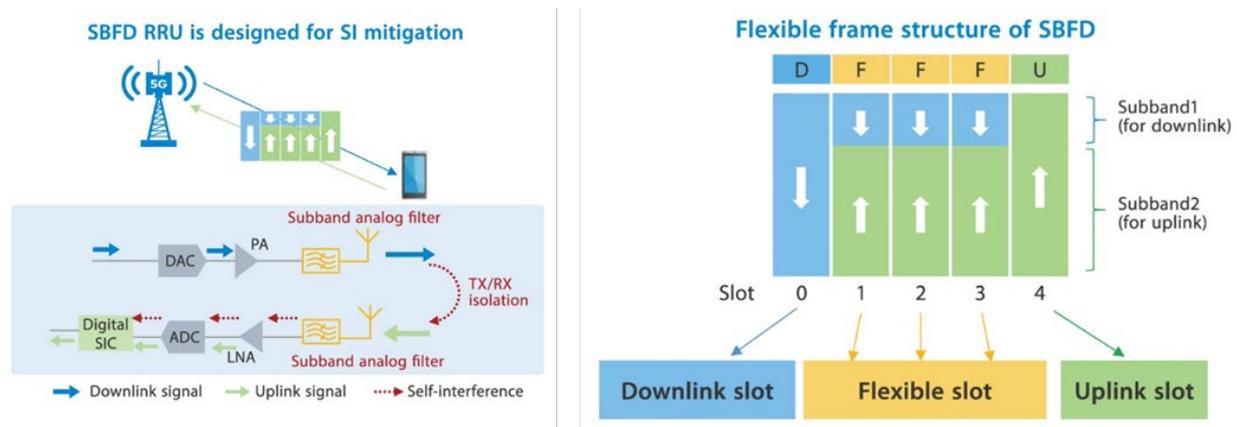

Figure 15. SBFD operation concept (SI: Self Interference, RRU: Remote Radio Unit).

In a mono-static ISAC scenario, where the transmitter and receiver are co-located, the sub-band full duplex scheme serves as a practical enabler for concurrent sensing and communication. By partitioning the available spectrum into non-overlapping sub-bands, SBFD allows one sub-band to be dedicated to downlink communication while another is used for sensing (e.g., radar signal reception), effectively mitigating the self-interference that would arise in a conventional full duplex setup. This is particularly important in mono-static ISAC systems, where the strong transmit signal can easily block weak reflections from sensed targets. SBFD provides frequency separation that enables simultaneous operation without the need for extreme levels of self-interference cancellation, preserving sensing accuracy and communication quality in shared hardware platforms (see Figure 16).

SystemVue provides a powerful environment for modeling and evaluating full duplex and SBFD schemes in the context of 6G. It supports realistic transceiver impairments such as non-linear PA behavior, phase noise, IQ imbalance, and RF front-end asymmetries that affect the effectiveness of SIC algorithms. Designers can simulate analog and digital SIC techniques, including adaptive filtering, active cancellation, and joint baseband/RF optimization. For SBFD, SystemVue allows flexible sub-band partitioning, coexistence testing, and interference modeling across sub-channels. Integrated waveform generation, channel modeling, and antenna array simulation further enable evaluation of practical deployment scenarios, including full duplex operation with massive MIMO and RIS-based systems. This comprehensive modeling capability makes SystemVue a critical tool for validating performance trade-offs and feasibility of duplexing schemes under realistic hardware constraints and propagation environments.
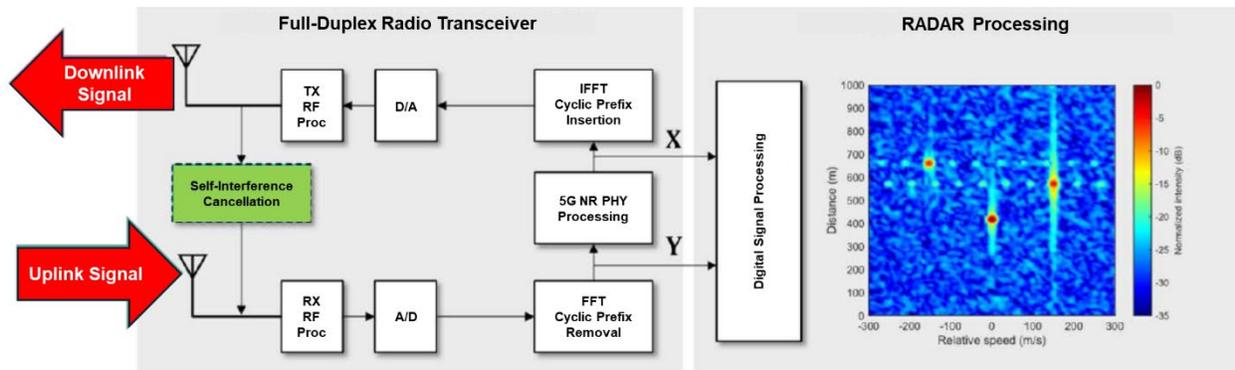
Figure 16. Full-Duplex mono-static sensing at a base station [1]

RF Digital Twin

A digital twin is a dynamic, real-time virtual replica of a physical system that simulates its properties, conditions, and behaviors using realistic models informed by live data. As illustrated in Figure 17, real-world measurements are ingested into simulation software, where outputs are computed either algorithmically or via machine learning. These simulated outputs are then compared to actual performance to assess operational accuracy. This process enables proactive fault detection, scenario exploration, and predictive maintenance by allowing engineers to virtually test various environmental and operating conditions before real-world deployment.
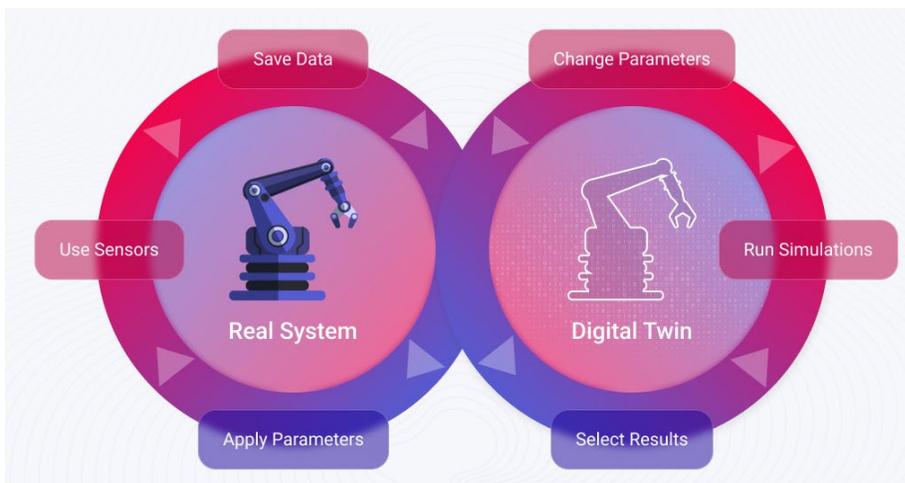

Figure 17. Illustration of the concept of digital twin [2]

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1 Samir-Mohamad Omar, Towards an OFDM Radar Waveform for Detection of Far Located Targets with Relatively Low Radar Cross Sections, Digital Signal Processing Volume 114, July 2021.
2 Best Readings in Digital Twins https://www.comsoc.org/publications/best-readings/digital-twins

For RF and antenna systems in 6G, a digital twin must accurately mirror physical behavior under realistic operating environments. This includes high-fidelity modeling of nonlinearities, noise, impedance mismatches, and mutual coupling in large-scale antenna arrays. The digital twin should also integrate with electromagnetic solvers to capture near-field and far-field radiation patterns and beamforming dynamics. It must simulate channel impairments such as mobility, Doppler shift, and interference, while supporting co-simulation across circuit, system, and channel domains. To be effective, the twin must scale with design complexity, support hardware-in-the-loop testing, leverage measured calibration data, and incorporate AI/ML for optimization. These features are critical for developing energy-efficient, robust, and adaptive systems for 6G applications.

Digital twins offer significant advantages in 6G development by enabling virtual prototyping under real-world conditions without costly or time-consuming physical testing. Designers can explore the impact of hardware impairments, dynamic channel variations, and multi-user interference on system performance with greater repeatability and precision. This capability is especially valuable for mission-critical applications like autonomous systems, smart infrastructure, and industrial automation. By enabling predictive analysis and early-stage optimization, digital twins enhance reliability, reduce development cycles, and lower the risk of field failures.

Keysight SystemVue stands out as a powerful platform for implementing RF digital twins in 6G system design. It delivers near-circuit-level accuracy for RF signal chains — including amplifiers, mixers, filters, and antennas — while supporting co-simulation of baseband processing, phased arrays, and propagation effects. Engineers can evaluate real-world impairments like nonlinearity, phase noise, and antenna coupling across time and frequency domains. Features such as DPD modeling, advanced waveform generation, and realistic RF impairments make SystemVue an ideal environment for holistic system validation and optimization.

SystemVue also bridges simulation and hardware by integrating seamlessly with Keysight's test instruments and EM tools such as ADS and RFPro. Figure 18 illustrates how SystemVue enables full digital twin workflows, including accurate modeling of beamformers, splitters, PCB trace layouts, and commercial RFICs. These virtual designs are validated with measured data—such as radiation patterns, gain, EVM, and noise density—ensuring simulation results correlate closely with physical performance.

This capability is essential for 6G development, where sub-THz operation, massive MIMO, and intelligent surfaces push traditional design tools to their limits. With predictive modeling and hardware-aware simulation, SystemVue empowers engineers to accelerate development cycles, improve design accuracy, and bring next-generation wireless technologies to market with confidence.
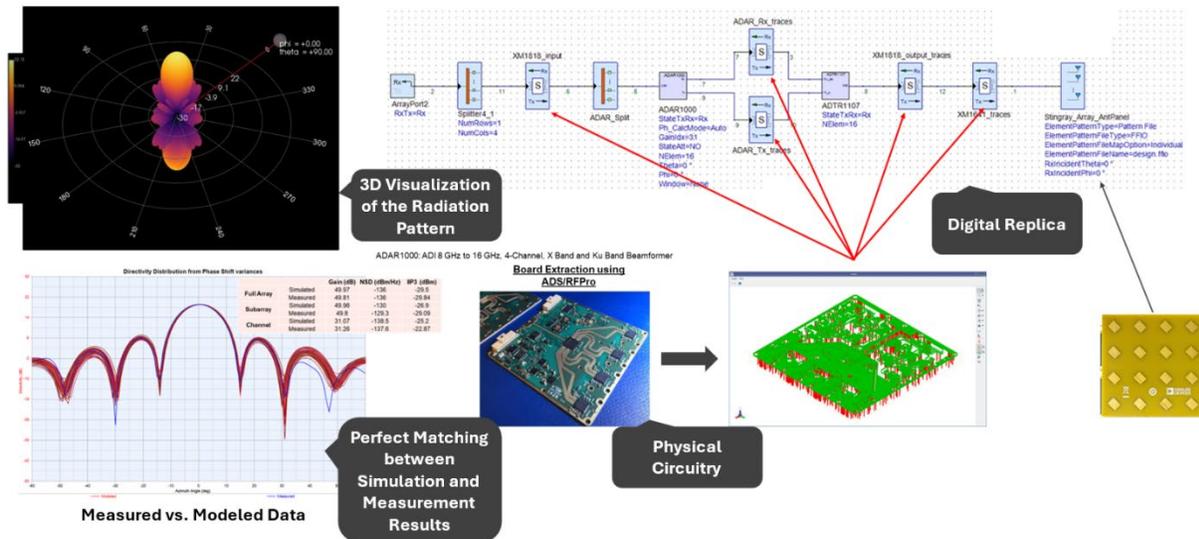
Figure 18. Example comparison of the characteristics of a physical circuit and its digital replica created by SystemVue.

AI-Based PA Linearization

Artificial Neural Network (ANN)-based power amplifier linearization employs AI-driven models to implement digital predistortion, effectively compensating for the nonlinear behavior of RF PAs. Traditional DPD techniques — such as memory polynomials or Volterra series — often fall short in handling the wide bandwidths, memory effects, and dynamic impairments present in modern 5G and 6G systems. ANNs, however, excel in modeling complex nonlinear functions and can learn the inverse behavior of the PA directly from measured or simulated data. The training process involves feeding a known baseband signal into the PA and recording its distorted output. These input-output pairs are then used to train an ANN — commonly a feedforward, time-delay, or convolutional network — to generate a predistortion mapping that compensates for gain compression, memory effects, and AM/AM and AM/PM distortion. Once trained, the ANN is embedded into the transmit path to modify incoming signals so that, after amplification, the output remains spectrally clean and linear.

In practical deployment, the trained ANN operates in real time on FPGA or DSP hardware, applying predistortion to the digital baseband signal before it reaches the PA. To maintain accuracy under varying environmental conditions (e.g., temperature shifts, aging, or load changes), adaptive schemes such as Indirect Learning Architecture (ILA), online learning, or reinforcement learning can be employed to continuously update the ANN weights. Compared to traditional DPD, ANN-based solutions offer greater adaptability, improved performance for wideband signals, and resilience to system-level variations. Similarly, AI-based Crest Factor Reduction (CFR) techniques use deep learning or recurrent neural networks to intelligently suppress signal peaks while preserving signal integrity and minimizing Adjacent Channel Leakage (ACLR) and Error Vector Magnitude (EVM). These AI-enhanced methods outperform conventional rule-based CFR strategies by dynamically adapting to waveform characteristics. Tools like Keysight SystemVue enable seamless integration of AI models into the RF design flow—supporting co-simulation, training with measured PA data, and closed-loop validation—thus empowering engineers to develop robust, power-efficient, and high-linearity transmitter chains for next-generation wireless systems.

ANN-based DPD workflow:

1. Data Collection: Transmit a known set of complex baseband signals through the PA and capture the corresponding distorted outputs.

2. Model Training: Train an ANN (e.g., a feedforward network with ReLU activation) to learn the inverse of the PA's nonlinear characteristics using the input-output pairs.

3. Deployment: Integrate the trained ANN into the transmission chain to apply real-time predistortion.

4. Performance Evaluation: Monitor key metrics such as EVM, ACLR, and spectral regrowth to assess linearization accuracy and adapt the model as needed.

Complementary to ANN-based DPD, Envelope Tracking (ET) is a key technique used to enhance power efficiency in RF power amplifiers, especially for high Peak-to-Average Power Ratio (PAPR) waveforms common in 5G and 6G systems. ET dynamically adjusts the supply voltage of the PA in real time based on the instantaneous amplitude (envelope) of the transmit signal, ensuring that the PA operates near its optimal efficiency point across varying power levels. This contrasts with traditional fixed-supply operation, which leads to significant power loss during low-amplitude signal periods. When combined with DPD, ET must be tightly coordinated to account for additional nonlinearities and memory effects introduced by the varying supply voltage. ANN-based models are well-suited to this task, as they can learn and compensate for the more complex, time-varying distortion behaviors inherent in ET-enabled PAs. By incorporating envelope tracking into the ANN-based DPD training and simulation loop—using tools like SystemVue—engineers can co-optimize linearity and efficiency, paving the way for energy-aware, high-performance transmitters in next-generation wireless systems.

Conclusions and Remarks

The transition to 6G presents a new set of challenges and opportunities that demand a holistic, end-to-end approach to wireless system design. This whitepaper highlighted how Keysight's SystemVue provides a comprehensive, high-fidelity modeling and simulation environment to support the development and validation of emerging 6G technologies. Through examples including ISAC, RIS, NTN, and sub-THz RF front-end modeling, we have shown that SystemVue functions as a powerful RF digital twin—bridging the gap between simulation and real-world performance.

As 6G evolves to unify communication, sensing, intelligence, and connectivity in extreme environments, system design tools must advance in parallel. SystemVue enables early architectural exploration, AI-assisted optimization, and hardware-in-the-loop validation to accelerate innovation while reducing risk and cost. By integrating circuit-level accuracy, advanced RF impairment modeling, and AI/ML-driven workflows, SystemVue empowers designers to make informed trade-offs and achieve first-pass success in complex 6G deployments. In this era of connected intelligence, such platforms are indispensable for translating cutting-edge concepts into deployable, scalable, and sustainable wireless systems.

References

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