6G AND ADVANCED ANTENNA SYSTEMS

How virtual twins are driving the development of next-generation communication networks

EXECUTIVE SUMMARY

This white paper explores the transition to 6G and how advanced antenna system design using virtual twins is a key enabler of ubiquitous connectivity—one of the stated goals for 6G. Building on 5G advancements, 6G aims to address current challenges such as limited 5G high-band adoption, while delivering higher data rates, improved coverage, and more reliable connectivity. The virtual twin promotes rapid 6G design exploration and on-time deployment.

Emerging technologies such as gigantic multiple input-multiple output (MIMO), meta-surfaces and dielectric gradient-index (GRIN) lenses are likely central to 6G's development. Gigantic MIMO increases subscriber bandwidth allocation while offering localization and sensing. Meta-surfaces, including reflective intelligent surfaces (RIS), actively steer signals to improve coverage, while GRIN lenses provide densification.

Virtual twins, powered by platforms like Dassault Systèmes' **3D**EXPERIENCE®, enable researchers to simulate and optimize systems before hardware development. Applications include antenna design, tower stability analysis and real-world performance assessments, ensuring designs meet key performance indicators (KPIs) and regulatory standards.

6G promises seamless connectivity for consumers, industries and cities. It aims to provide robust service in dense urban areas and challenging environments. Continued collaboration, research and simulation-driven development will ensure a reliable and scalable 6G network, driving the next generation of wireless communication.

What is a virtual twin?
A model is only helpful if its behavior matches that of the real-world system it represents. A virtual twin combines all the available data about a system into a single model to produce as accurate a representation as possible of the system. A validated virtual twin gives users confidence that the simulation results correspond to actual behavior.

INTRODUCTION

It may seem as if 5G has only just arrived, but it was launched in 2019 and has undergone several upgrades since then. The latest upgrade, Release 18–5G Advanced, was finalized in 2024 and includes enhanced support for industrial operations, positioning and satellite connectivity. Two more releases (19 and 20) are anticipated by the end of the decade when IMT-2030[1] is expected to be implemented. IMT-2030 will define a new framework and technologies to meet demand and user expectations and this will become the sixth generation of mobile communications or 6G. Discussions and standardization efforts for IMT-2030 and 6G started in 2024[2].

Nothing stands still in the communication world and researchers are actively exploring new technologies to improve wireless communications for the next generation. Although 6G may not be available for several more years, novel techniques, materials, new frequency bands and areas such as artificial intelligence are under active investigation. Proposed capabilities and use cases for wireless technologies are increasing beyond consumer handsets to the manufacturing floor, vehicle communications and the "internet of everything." Seamless connectivity should become an expected feature of our personal and business lives. However, the early days of 5G saw a great deal of marketing hype and growth was not as strong as expected in some areas. For example, industrial 5G private network uptake has been slow. The later stages of 5G and into 6G will require compelling use cases and significant benefits to drive change and growth. Using a virtual twin for the research phases will help validate the technology and applications before hardware development.

6G AND HYPER-CONNECTIVITY

As 5G matures, several exciting antenna and connectivity technologies are under active investigation, some of which will make it into the 6G standards. Large OEMs, start-ups and research groups are all active in this area, often using virtual twins to simulate technical effectiveness. The nature of the work means that only a few key technologies offer sufficient advantages and cost-effectiveness to make it through. We'll examine the most promising technologies and how the virtual twin and multiphysics simulation are helping to push the boundaries of what's possible.

Improved Coverage

Meta-surfaces such as RIS and dielectric lenses are likely to be part of new 6G network infrastructure. Meta-surface technologies can actively shape and direct beams into urban shadow areas or building interiors, helping to provide seamless, high-capacity coverage. Dielectric lenses may be used for densification—the effective coverage of densely populated urban areas or venues.

1. Framework and overall objectives of the future development of IMT (International Mobile Telecommunications) for 2030 and beyond https://www.itu.int/dms_pub/itu-d/oth/07/31/D07310000090015PDFE.pdf

2. WG SA1 6G Use Case Workshop https://www.3gpp.org/news-events/3gpp-news/sa1-6g

Improved Data Rates and Localization

Due to likely increases in operating frequencies, the density of elements within base station antenna arrays can increase, leading from massive MIMO to gigantic MIMO. This allows a single array and its subarrays to address a larger number of end-users with narrower beam focusing and improved data rates. 3D localization and sensing will also be improved, particularly if the subarrays are physically separated on the tower but coordinated as one antenna, as proposed by Emil Björnson et al.[3] Virtual twin simulation allows deeper investigation of these types of novel configurations.

New Frequency Bands

Frequencies up to the terahertz range have been proposed for 6G. This has the potential to offer massive capacity. However, the band has very limited range and is easily attenuated or blocked by objects in the signal path. In fact, 5G mm-wave or high-band 5G at 24 GHz and above requires dense tower deployments to be effective and is struggling commercially. It's possible that it never becomes commercially successful. South Korea closed down its 5G mm-wave networks in 2023 and Europe has not started deployment. More likely new frequency bands for 6G are in the 7-GHz range to start, with extensions up to 24 GHz later. On its own, the 7-GHz band does not offer a great deal more capacity than mid-band 5G, but combined with the technologies mentioned above, the extra capacity can be significant.

Sensing Networks

6G may enable situationally aware devices that use sensors and machine learning. This allows them to sense and map the environment and effectively assist the network to establish a good connection. General sensing of the environment through a 6G network may also be possible. For example, a car accident or someone falling on the sidewalk could be detected. The overall effect for consumers, industrial users and other connected objects such as drones and vehicles, should be a safer environment with a stable and seamless connection as they move through complex outdoor and indoor environments.

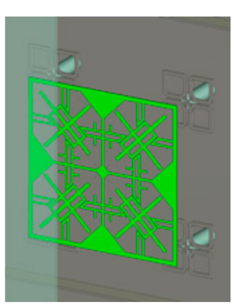
6G ANTENNA TECHNOLOGIES IN DETAIL

Here, we examine some of the most promising improvements to antenna systems and related components and materials. All of these are under active investigation to improve mobile communication coverage and data rates for the next generation.

Shared Aperture Arrays and Gigantic MIMO

To reduce costs and environmental impact, the new generation of antennas will be added to existing tower infrastructure. However, legacy cellular generations and backhaul communications often take up all the available space. In addition, more high-mounted antenna arrays and equipment can cause instability and wind-loading concerns. A solution is to extend the use of shared aperture arrays (FIGURE 1), where antenna arrays are stacked on top of each other within the same housing. To be effective, the front array must be transparent to the array behind.

Implementing 6G will require redesigning the shared aperture arrays and virtual twin simulation will help accelerate this complex process, particularly considering the density and complexity of gigantic MIMO arrays. FIGURE 2 shows the results simulated using CST Studio Suite on the **3D**EXPERIENCE platform.



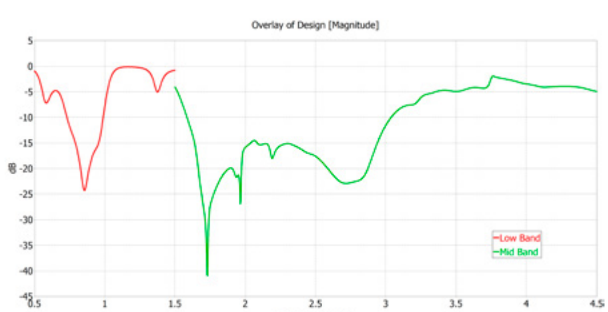


FIGURE 1: Example of a shared aperture array.

FIGURE 2: A shared aperture array simulation showing the distinct operating bands for two arrays.

3. Enabling 6G Performance in the Upper Mid-Band by Transitioning From Massive to Gigantic MIMO https://arxiv.org/pdf/2407.05630

Gigantic MIMO is an extension of massive MIMO and it increases the number of elements in the arrays while keeping an identical physical footprint. This is possible due to the higher proposed frequency bands of 6G, allowing smaller elements and element spacing. It's likely that the increased capacity of 6G will come primarily from these larger arrays allowing greater spatial multiplexing. Individual end-users are addressed with narrower beams, meaning less sharing of their data capacity. Combining the increased spectrum capacity in the 7-GHz band with the increase in spatial multiplexing, should allow 6G to offer up to 10x the data capacity of 5G in its first iteration.

Dielectric Lenses

Dielectric lenses are another potential tool in the 6G arsenal to improve coverage at higher frequencies which, as we have seen, can suffer from path loss and blockage. Dielectric lenses for antennas are components that operate analogously to their optical counterparts. They change the speed of the wave as it travels through them.

GRIN lenses are a subcategory of dielectric lenses. They are advanced dielectric components to enhance signal transmission and reception. Unlike traditional lenses with uniform refractive indices and a fixed shape, GRIN lenses can have varying 3D-printed shapes with a refractive index that varies gradually across their structure (FIGURE 3). This gradient allows for precise control over the electromagnetic wave propagation, making GRIN lenses highly effective for directing and focusing signals (FIGURE 4). In combination with massive or gigantic MIMO arrays, lenses can shape the beams, increase the field of view and reduce power requirements—reducing the array signal processing load.

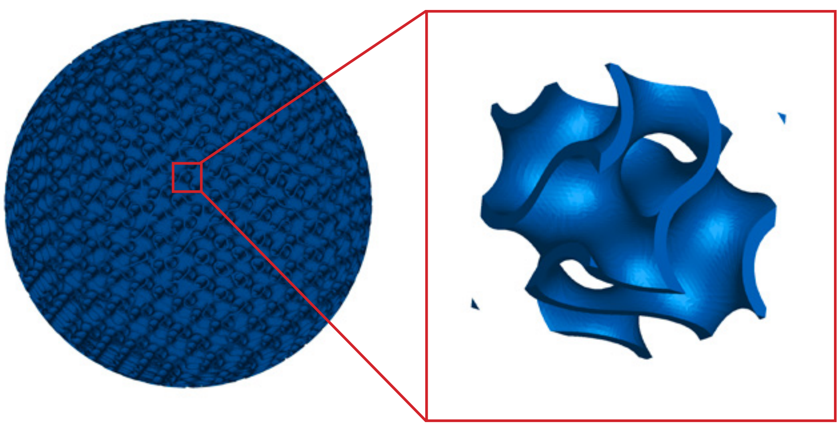


FIGURE 3: A spherical GRIN lens and one of its constituent cells.

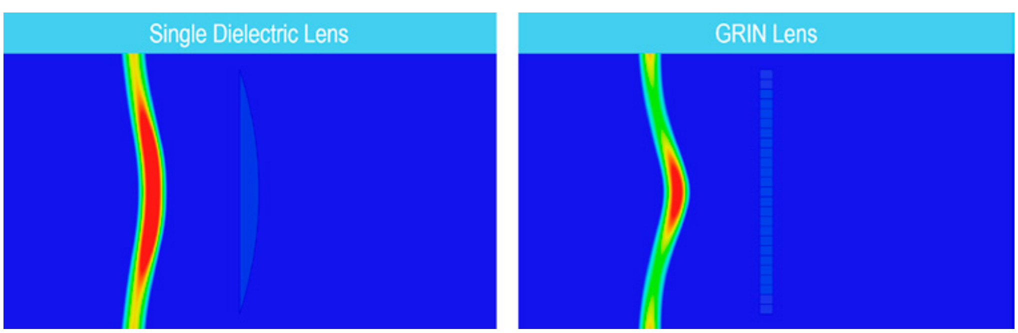


FIGURE 4. Similar to a single dielectric lens, a GRIN lens can focus and direct energy, but with much more flexibility in its shape and properties.

Using the solvers and space-mapping capabilities of CST Studio Suite on the **3D**EXPERIENCE platform enables accurate simulation of this complex technology at every level, from unit cells to walk-test verification. This combination of influences has made GRIN lens technology[4] the focus of exciting activity in 6G network design.

4. GRIN Lens Antennas for 6G: Background, Simulation and Fabrication https://events.3ds.com/grin-lens-antenna-simulation-fabrication

Meta-Surfaces and Reflective Intelligent Surfaces (RIS)

Massive and gigantic MIMO systems have greatly increased network data capacity by exploiting multipath effects for spatial diversity. However, ensuring reliable network coverage for end-users remains a challenge, particularly in environments where signals encounter obstacles such as buildings and foliage. Effective coverage depends largely on the frequency band and environmental conditions. Frequencies below 1 GHz can penetrate obstacles effectively, but at higher frequencies—such as those proposed for 6G, particularly above 28 GHz—signals are more easily blocked or absorbed.

In these high-frequency bands, maintaining coverage without direct line-of-sight (LOS) becomes difficult. While increasing the density of base stations could improve coverage, this solution is prohibitively expensive and inefficient. A more promising approach involves creating deterministic signal propagation models by adapting the environment itself to assist in channel formation. This is where reconfigurable reflective meta-surfaces come into play as a key enabler for 6G networks.

What Are Reconfigurable Reflective Meta-Surfaces?

Meta-surfaces are engineered artificial surfaces with electromagnetic properties that go beyond those of natural materials. They consist of regularly arranged elements, typically spaced less than half a wavelength apart. These surfaces can be powered or semi-passive:

1. Powered Meta-Surfaces (Holographic Antennas):
   By tuning the individual elements, powered meta-surfaces can dynamically direct electromagnetic waves with high precision. These operate similarly to traditional antenna arrays but use continuous or quasi-continuous surfaces to perform dynamic wavefront synthesis.

2. Passive Reflective Intelligent Surfaces (RIS):
   In a passive setup, the meta-surface elements, often equipped with tunable diodes, reflect rather than radiate energy. By adjusting the phase and direction of reflected waves, RIS can steer signals toward end-users efficiently. Unlike traditional MIMO systems, which require active power for transmitting signals, RIS operates with minimal power, primarily for tuning its elements.

Leveraging RIS for 6G Coverage

Reflective intelligent surfaces have significant potential to address coverage challenges in 6G, particularly in high-frequency bands. By strategically deploying RIS, the environment itself becomes an integral part of the signal propagation process. These surfaces can reflect and steer incident beams to:

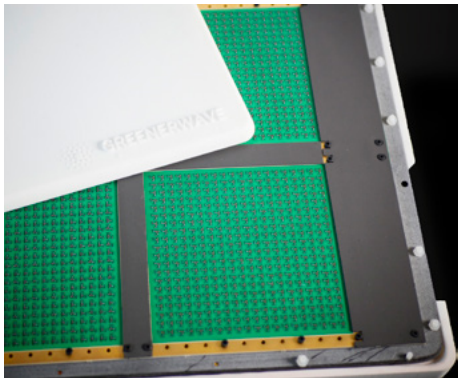
- Fill shadowed regions, both indoors and outdoors.
- Extend coverage at the edges of cells.
- Enhance signal reliability and reduce fading caused by multipath propagation.

For example, RIS panels integrated into building facades or street infrastructure could improve coverage for pedestrians in dense urban areas. Similarly, embedding RIS into walls, ceilings, and windows within smart environments[5] could enhance connectivity for indoor users.

RIS has several advantages over traditional MIMO systems including energy efficiency, cost-effectiveness and easy incorporation into existing infrastructure. The main advantage is more predictable signal paths. Unlike traditional systems that rely on probabilistic models of multipath propagation, RIS enables deterministic channel formation, leading to robust and predictable communication links.

There are challenges to deployment including scalability, interference management, planning complexity and the accuracy of the environmental models. A simulation virtual twin of the RIS and the local environment is a major resource for the research and design phases, helping to overcome challenges and provide an optimal solution.

5. Multi-Functional Reconfigurable Intelligent Surfaces for Enhanced Sensing and Communication
https://pmc.ncbi.nlm.nih.gov/articles/PMC10610703/#:~:text=Then%2C%20by%20strategically%20controlling%20the,dual%2C%20or%20quad%2Dbeam



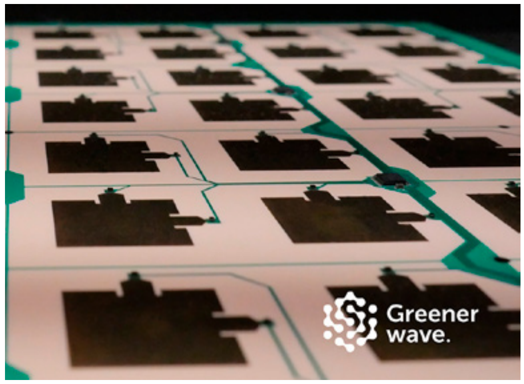


FIGURE 5: Prototype RIS (left), detail of a RIS surface (right), courtesy of Greenerwave.

6G FOR THE REAL WORLD

The goal in developing 6G is to provide efficient, consistent end-to-end coverage, even as the number of devices, applications and usage scenarios continues to grow. The virtual twin and simulation is pivotal in enabling organizations to test the viability of new technology and to help develop the required standards. The **3D**EXPERIENCE platform enables global collaboration based on a central virtual-twin data model exploiting cloud-based high-performance computing for simulation. This helps to systematically speed up the development and certification process compared to typical file-based processes.

Dassault Systèmes works closely with all stakeholders in the wireless communication ecosystem to develop optimal workflows, best practices and automation to help meet the challenges and lead to the best possible design outcomes. Simulation has played a large and increasing role in the design of legacy cellular equipment and devices. For 6G we expect the role of simulation and the virtual twin to be even more significant.

Here are some examples of applications where Dassault Systèmes is providing best-in-class solutions that are laying the foundations of 6G.

Tower Multiphysics

6G will require new transmission equipment and antennas which will be installed on existing communication towers. Even using shared aperture designs, there may be more weight high up on the tower. Stress and wind loading effects due to the additional weight must be considered to ensure the integrity of the tower under all possible conditions (FIGURE 7).

Modeling and simulation of both wind effects and structural dynamics, as well as the connection between the two, are possible on the **3D**EXPERIENCE platform. A virtual twin of the tower helps tower operators and network providers ensure that they install new equipment safely. A single data model can be maintained through the design phases and across the multiphysics simulations, ensuring all stakeholders are fully informed and working with the latest update (FIGURE 6).

Using the virtual twin, additional physics can be simulated, including the installed performance of the 6G antenna systems and the electromagnetic exposure risks for maintenance staff who work on the towers (FIGURE 8).

Virtual Walk Test: Urban Environment

New equipment might work perfectly in the lab or in ideal conditions, but the success of 6G depends on how well it performs in the real world. Creating a virtual twin of the base station, tower, antennas and nearby city blocks (FIGURE 9) enables detailed performance analysis as users move through the city with their mobile devices. Fixed wireless connections to city infrastructure can also be assessed.

Virtual twin simulation provides a detailed picture of the local base station coverage and potential connection quality in the parts of the environment where people will pass through. This helps network providers to identify any issues and take steps to address them before installation (FIGURE 10).

By simulating the coverage of typical equipment on the towers, 6G planners can explore approaches to deliver improvements including the positioning of new arrays, RIS and lenses.

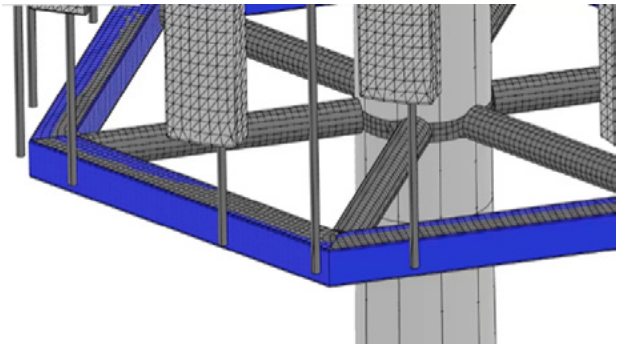


FIGURE 6: A geometric model of the existing tower is used to create a finite element representation, which is automatically meshed. Any changes to the geometry are reflected in the mesh.

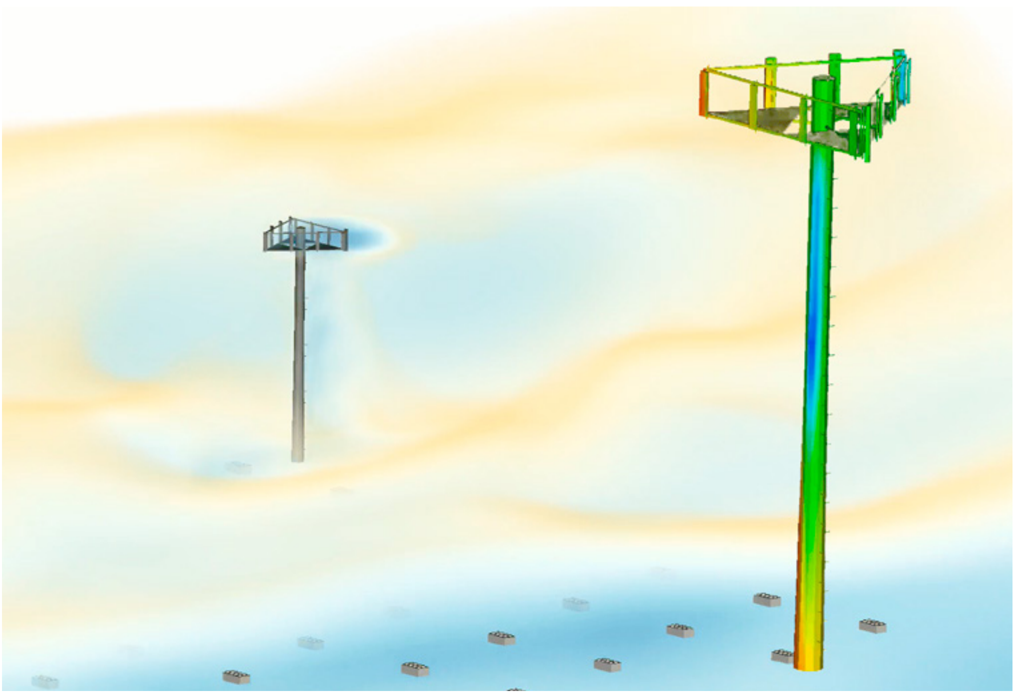
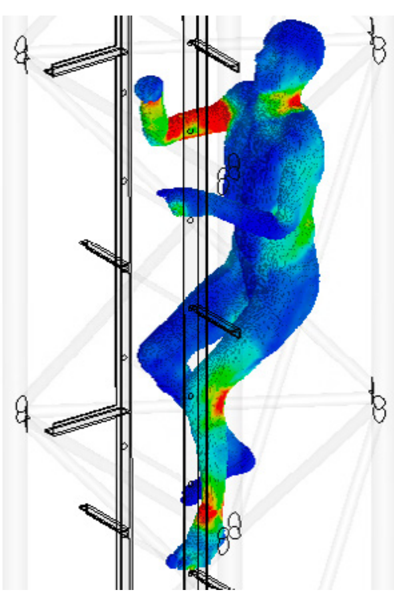


FIGURE 7: Simulating the tower under various conditions provides insights into structural stability as new equipment is added. In this example, the planner is mapping the pressures and stresses that affect the tower in turbulent winds.



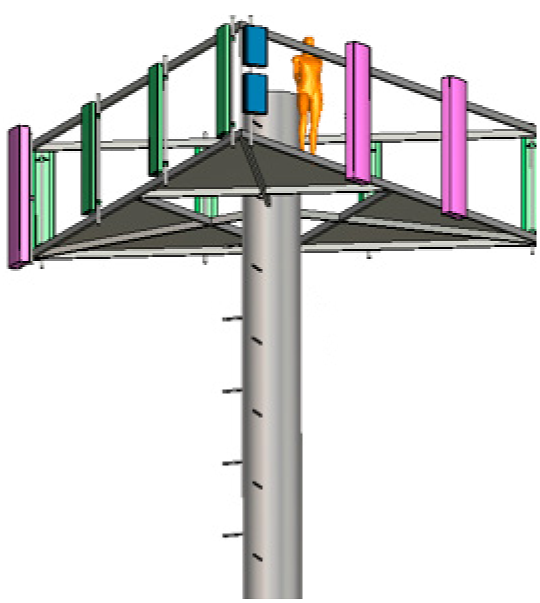
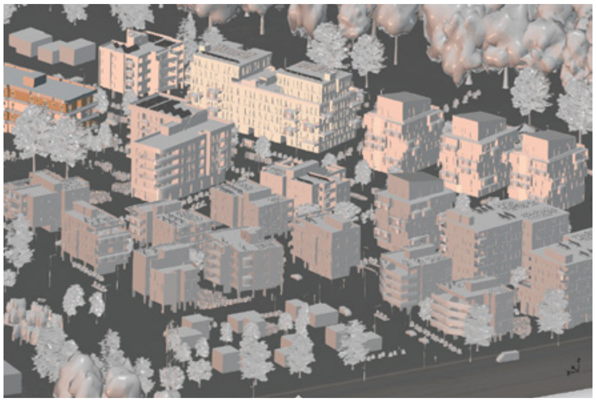


FIGURE 8: An electromagnetic simulation of the tower in operation can provide details of how much power is absorbed by a maintenance worker. This helps ensure that the SAR (specific absorption rate) meets regulatory requirements in accessible locations.



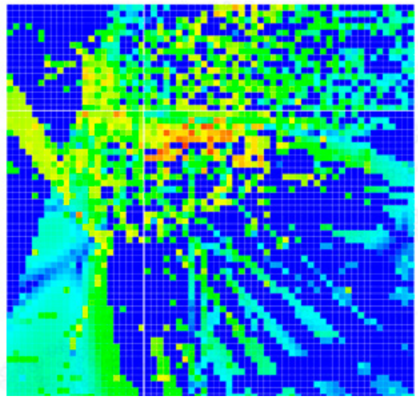


FIGURE 9 (left): City downtown area virtual twin model including the base station, buildings and the street environment.

FIGURE 10 (right): Cellular coverage in an urban environment. Plot shows received power.

Dense Population Areas

City planners and network operators may have difficulty providing good service to all subscribers in densely populated areas, such as near a transport link or in a stadium. The problem can be particularly acute around large temporary gatherings, such as outdoor events.

Ensuring good connectivity for large groups of people in all types of scenarios will be one of the goals for 6G. GRIN lens antennas for densification, as shown in FIGURE 11, are one possible solution. This lens has been designed using figures of merit for the required system performance. The simulation shows the farfield of the antenna system in its planned location, with additional KPIs available such as received power, signal-to-noise interference ratio and exposure. To improve the installation's performance, variations in parameters such as the antenna's positioning and the tilt angles of the beams can be explored.

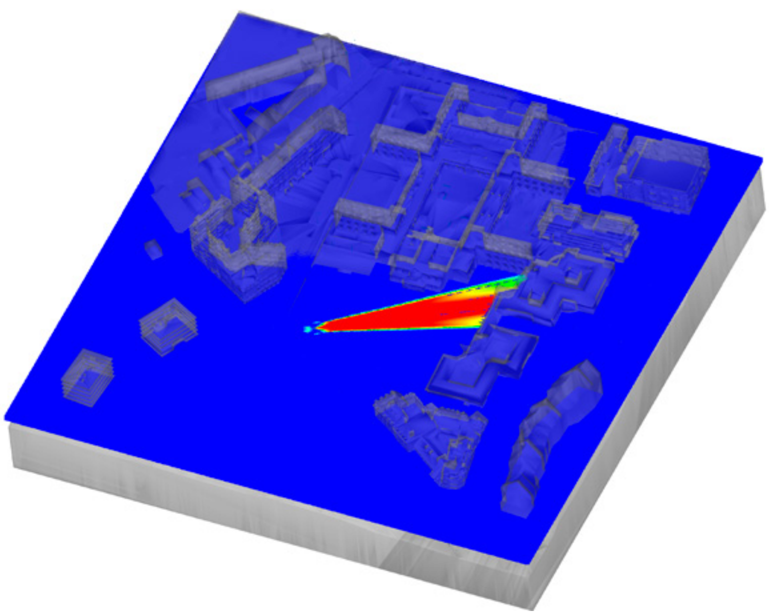


FIGURE 11: GRIN lens antenna and farfield

CREATE A 6G NETWORK WITH A VIRTUAL TWIN

6G research is well underway and standards bodies are already laying the foundations for the first implementation. Current research in advanced antenna systems, materials and techniques looks very promising. It's likely that meta-surfaces within holographic antennas or reflective surfaces, gigantic MIMO arrays, shared aperture arrays and dielectric GRIN lenses will play major parts in the 6G future.

Ensuring that installations work as expected and that all physics effects are considered will be critical. A virtual twin offers researchers and developers a way to explore options and new methods rapidly before hardware is built or installed. This will help ensure that real-world KPIs are met and systems pass regulatory scrutiny the first time.

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