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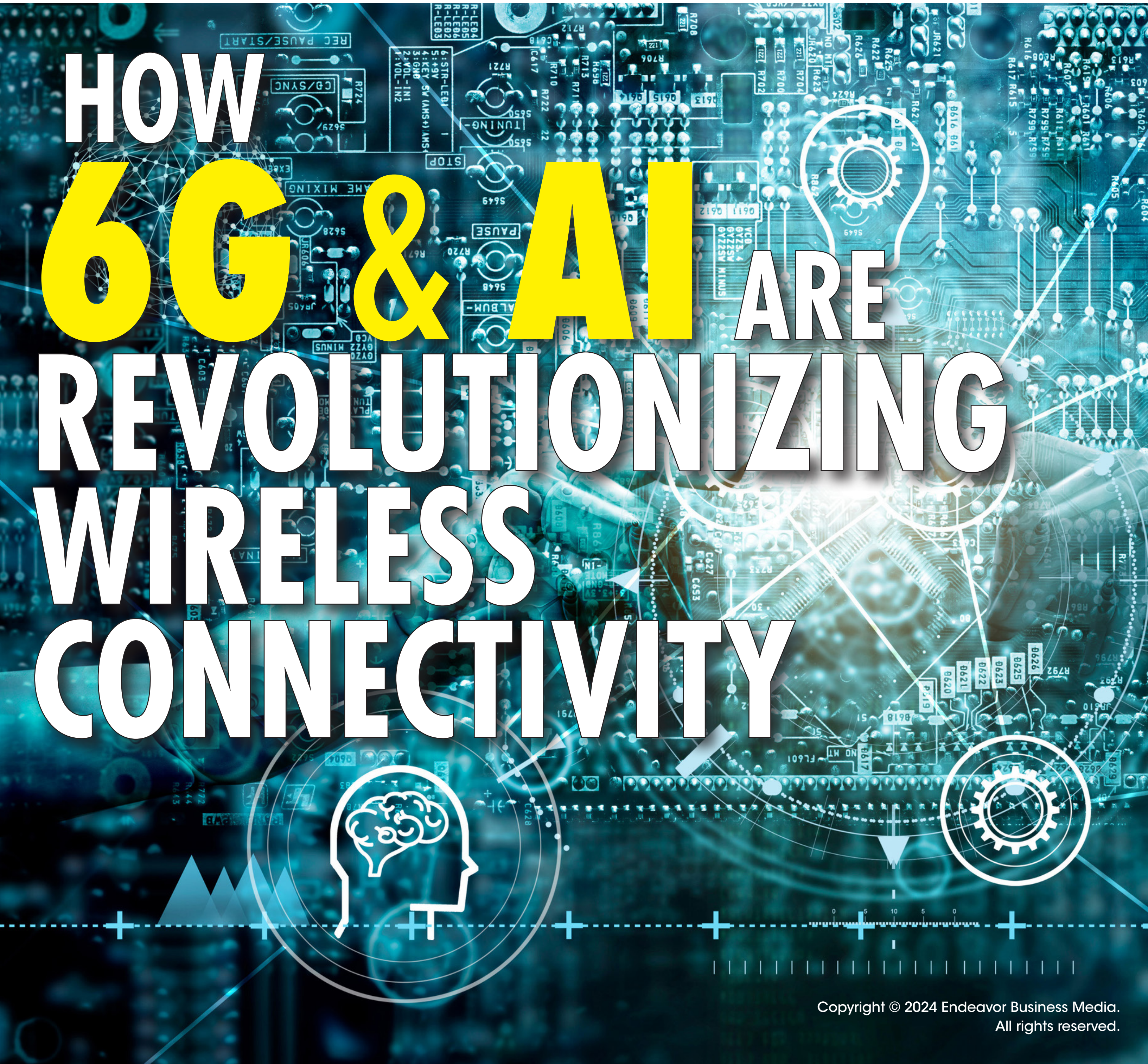
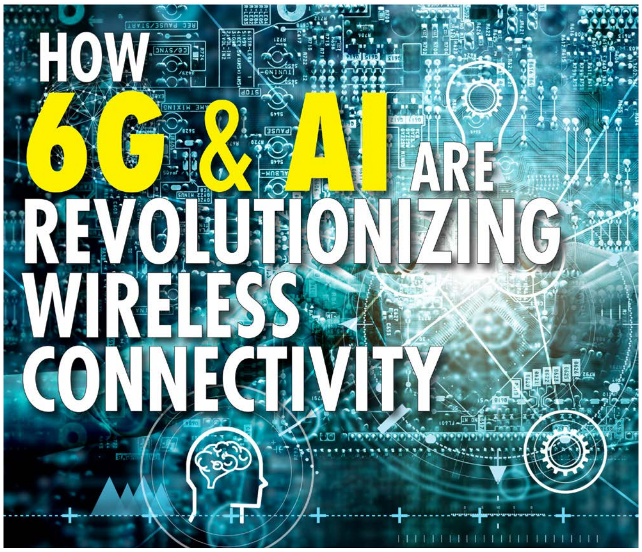


HOW 6G & AI ARE REVOLUTIONIZING WIRELESS CONNECTIVITY

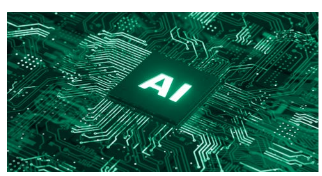


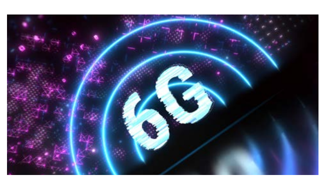
Alix Paultre
Editor-at-Large
Electronic Design, Microwaves & RF

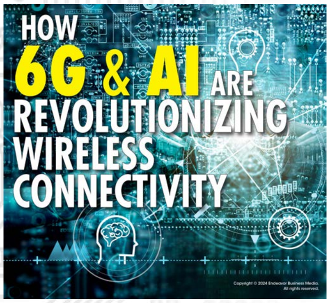
The continually expanding adoption of wireless communications is driving advances in mobile systems and their related infrastructures. The next generation of the cellular ecosystem will leverage non-terrestrial networks using low-Earth-orbit (LEO) satellites. This will be augmented with AI, presenting challenges to the engineering community in the areas of time, model reliability, data quality, and training.

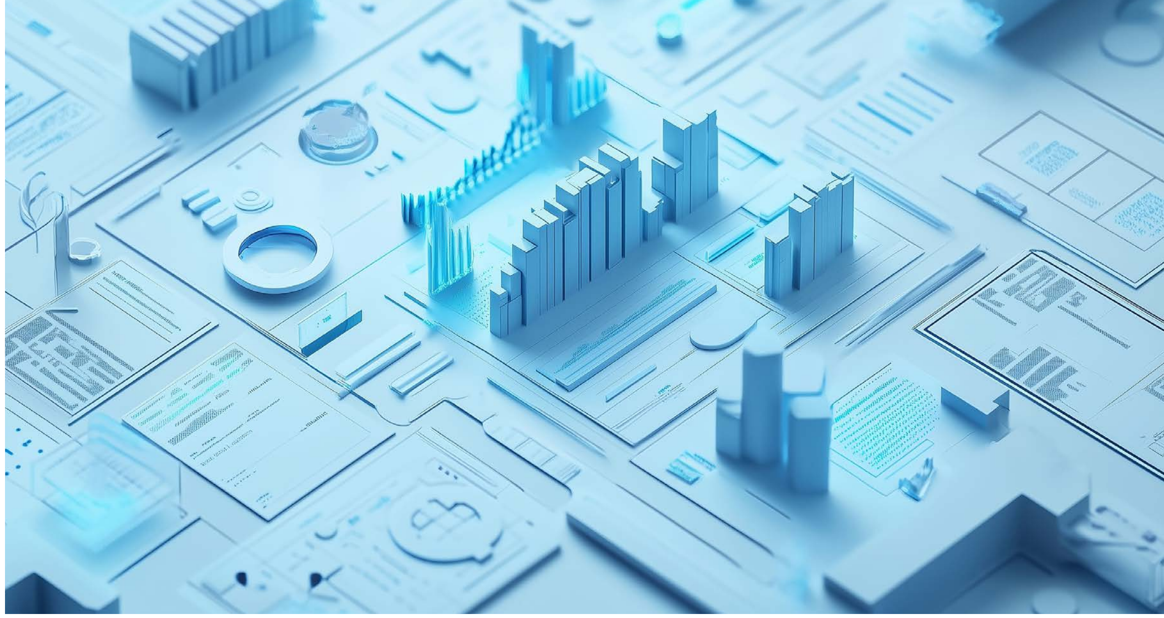
The latest development in the evolution of the mobile wireless communication infrastructure, 6G will provide inclusive and sustainable connectivity. It will substantially improve the performance of current 5G communications systems by operating faster and handling more bandwidth with lower latencies. The resulting enhanced connectivity could foment new applications in areas such as virtual and augmented reality, AI, connected systems, ubiquitous coverage through non-terrestrial networks, and others.

CONTENTS









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CHAPTER 1:

The LICRIS Research Project: Building the 6G Radio Channel

DR. TARO EICHLER, Technology Manager, Wireless Communication 5G/6G and Photonics, *Rohde & Schwarz*

Reconfigurable intelligent surfaces (RIS) will be an important technology pillar of the next 6G mobile communications standard. The objective is to use RIS to actively control radio channels, which until now have always been passive.

Even though the next mobile communications standard is still a few years away from introduction, we already know two things: 6G will enable new use cases and it will increase wireless communications between devices.

To open up more bandwidth, 6G uses parts of the higher and largely unused frequency spectrum, but higher attenuation and increased shadowing from buildings will also be factors during signal transmission. Both reduce network coverage. More transmitting antennas can compensate for the attenuation and shadowing, though only with greater power consumption.

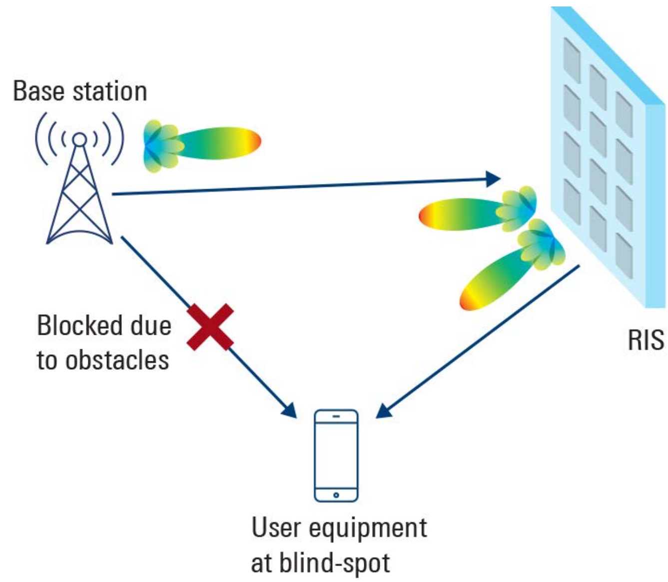
Another option is to modify how radio waves are propagated. Reconfigurable intelligent surfaces (RIS) hold a lot of promise. Suspending them from building facades, they can control the reflection of 6G radio waves to provide sufficient network coverage with far fewer transmitting antennas and far greater energy efficiency.

Beyond the Shannon Model

The Shannon model is the classic transmitter-receiver model used in communications engineering and assumes that a radio channel is a fixed quantity. This model focuses on encoding and decoding processes to maximize data throughput.

RIS can be used to actively adapt the radio channel during operation for the first time so that the channel is no longer passive. This opens the door to completely new optimization methods for radio communications far beyond the familiar territory of the Shannon model.

Radio channels and wave propagation are generally regarded as constant. Radio channels were fixed, for example, when passing through the walls of a building indoors. RIS now makes it possible to actively reflect and target radio channels and wave propa-



1. Mobile communications in the FR2 band are sensitive to obstacles in the transmission path. RIS can eliminate such gaps in network coverage.

gation for better coverage in the future.

Reconfigurable Intelligent Surfaces

RIS are antennas and integrated circuits that use special diodes or liquid crystals. They form a flat structure and can be configured to reflect incoming radio waves and forward them to receivers. Compared to classic RF amplifiers (repeaters) that contain a transmitter and receiver, RIS are cheaper to purchase and more efficient to operate.

Current development projects use RIS as passive components that simply reflect signals, with no amplification. We observe the frequency range below 6 GHz (FR1) or the millimeter-wave range (FR2). Using the surfaces as active signal amplifiers might be interesting, but higher-energy demands and construction costs mean that this use isn't a top priority.

In general, RIS are best in densely populated areas and in industrial environments. They improve spectral efficiency and make it easier to generate and manage directional radio beams. When radio transmission requirements change, the RIS adjusts radio channels during operation. When installed on a building facade, an RIS will direct mobile communications into streets and interior spaces—areas where cellular coverage has been difficult.

Figure 1 shows how RIS can increase network coverage when the line of sight between the transmitter and receiver is blocked. This will apply to both indoor and outdoor scenarios in the future. Also important to the mobile communications industry: RIS can improve indoor base-station signal transmissions by integrating them into window glass as meta-lenses.[1] RIS are best installed close to the transmitter or close to the receiver to effectively minimize the loss of very-high-frequency signals (FR2) over the transmission path.

The LICRIS Project

The 6G Liquid Crystal Reconfigurable Intelligent Surfaces (LICRIS) project is developing RIS using liquid crystals.[2] These are better in the high-frequency ranges than semiconductors (also an option).

The project is funded by the German Federal Ministry of Education and Research (BMBF) and covers phases for developing new liquid-crystal materials, constructing RIS, and testing them in a mobile radio test network. The final step will place 6G LICRIS technology in a real network environment to demonstrate data transmission from one device to another (end-to-end data transmission).

Metamaterials in the RF Range

To keep power consumption low, RIS uses metamaterials to reflect electromagnetic waves. Metamaterials have properties that go beyond those of natural materials. In optics, metamaterials can have a negative refractive index (natural materials always have a positive refractive index). They're used in lenses with very high imaging quality or, more experimentally, to guide light around objects to act as a cloaking device. RIS metamaterials have excellent electromagnetic properties in the RF range.

Metamaterials have certain basic structures called meta-atoms. The geometry and arrangement of meta-atoms determine the properties of a metamaterial—a real advantage since both can be controlled in the manufacturing process. The metamaterial properties can be tailored to a specific application.

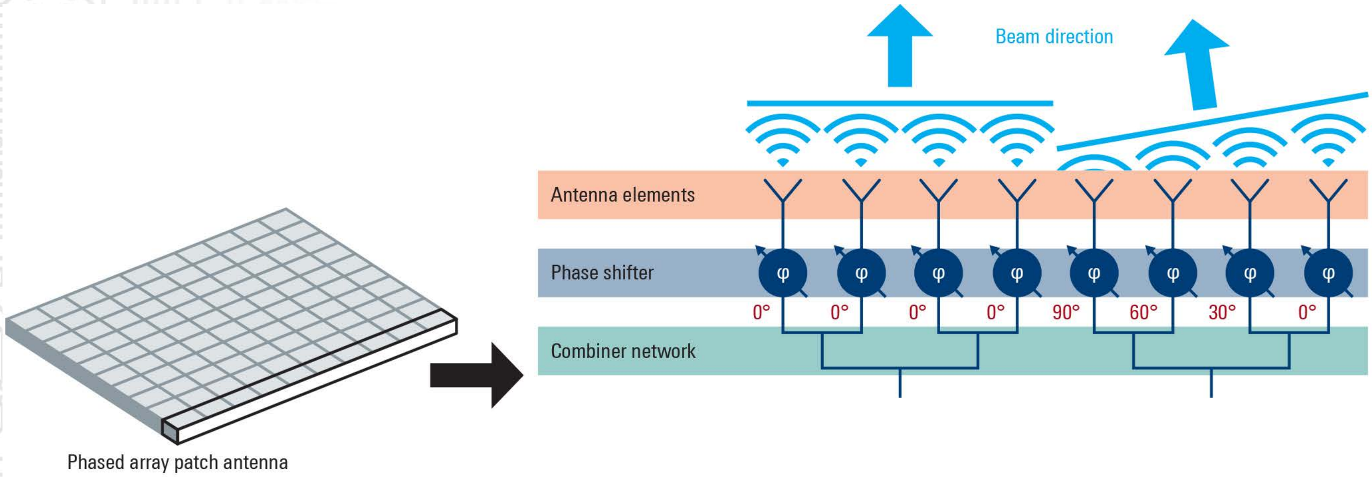
Meta-atoms are dimensioned to the application and always have wavelengths shorter than those of the signals reflected by the metamaterial. Light has a short wavelength and requires much smaller meta-atoms than radio signals, which have longer wavelengths.

Metamaterials can influence the propagation of electromagnetic waves in a way that's not possible with any other material. As a result, metamaterials give researchers an enormous amount of freedom when designing RIS and can improve properties such as the reflection, absorption, and transmission of electromagnetic waves.[3]

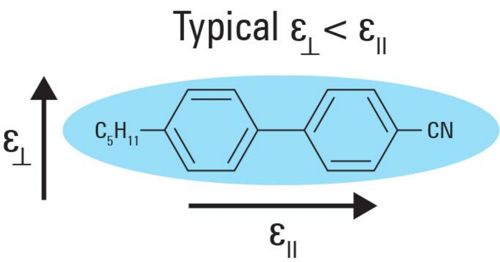
Liquid Crystals for RF Applications

Liquid crystals are a mature technology, which is a major advantage. Liquid crystals have been used in PC monitors and smartphone screens for decades. Their electrical control methods are well known, and the industry has mastered production of large-area liquid-crystal layers.

The technology is now being transferred to the RF sector. For example, liquid crystals are used in smart antennas.[2] Not only can they change the polarization of light, they're also capable of changing effective capacitor permittivity or capacitance. They're perfect for setting up phase shifters for directional RF antennas. Similar to screen pixels, phase-shifter pixels can be constructed and combined to form large-area directional antenna arrays or large RIS. **Figure 2** shows one such setup.



2. Flat phased-array directional antenna (left) consisting of many identical antenna elements in a square arrangement. Phase shifters are the central components, controlling the phase of each antenna element and generating the directional effect (right).



3. Example of a rod-shaped molecule in a liquid crystal. The anisotropic molecular shape leads to anisotropic physical properties such as the different electrical permittivity ε in parallel and perpendicular directions of incidence.

Liquid crystals were discovered in 1888 by Friedrich Reinitzer, who recognized them as a previously unknown phase of liquids. He was surprised to discover that their physical properties are also anisotropic (direction-dependent) in the liquid state, which until then had been considered a classic characteristic of solid crystal structures.

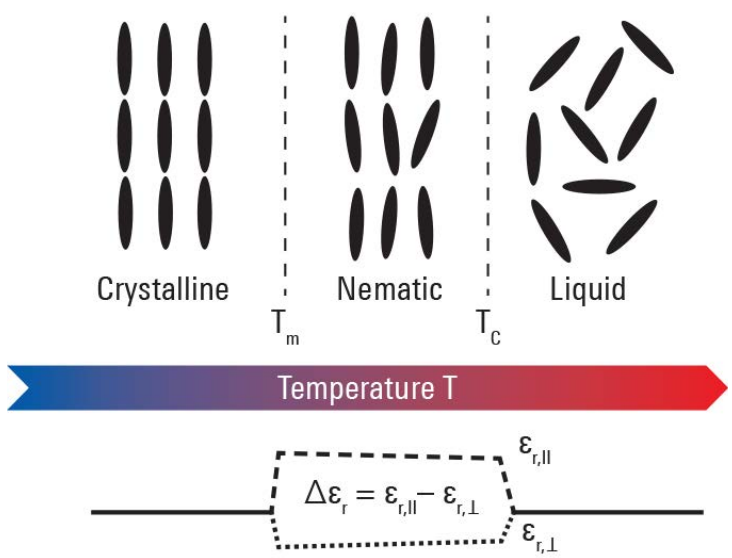
Today, many different classes of liquid crystals are known, and the underlying mechanisms are well understood.[6] This research was so fruitful and fundamental that Pierre-Gilles de Gennes was awarded the Nobel Prize in Physics in 1991.

Their anisotropy is due to rod-shaped molecules (**Fig. 3**), which are uniformly oriented in the liquid-crystalline phase and form an axis. **Figure 4** illustrates the nematic phase that occurs in the class of thermotropic liquid crystals. Liquid-crystal displays (LCDs) use this type of liquid crystal. In this case, anisotropy refers to the fact that the extent to which the nematic liquid crystals change the polarization of an electromagnetic wave (in this case, light from the LCD backlight) depends on the angle at which the wave strikes the axis.

In an LCD, an electric field changes the orientation of this axis to change the polarization direction of the light in a controlled manner. The liquid crystals are located between two polarization filters arranged perpendicular to one another and act like a light valve that controls the brightness of the individual display pixels (**Fig. 5**). The Merck Group in Darmstadt, Germany, the global market leader in the production of liquid crystals, is one of the partners in the 6G LICRIS project.

Two RIS Variants

The 6G LICRIS project is developing two RIS versions that work on the principle of phased-array directional antennas. The first type is for high frequencies from 26 to 27 GHz



4. Thermotropic liquid crystals change their phase depending on the temperature. At the melting point T_m, the crystalline material passes into the nematic phase and turbidity sets in. At the transparency point T_C, the uniform orientation of the molecules is lost and the liquid becomes transparent. One current research objective is to create liquid-crystal mixtures that express their "tunability."

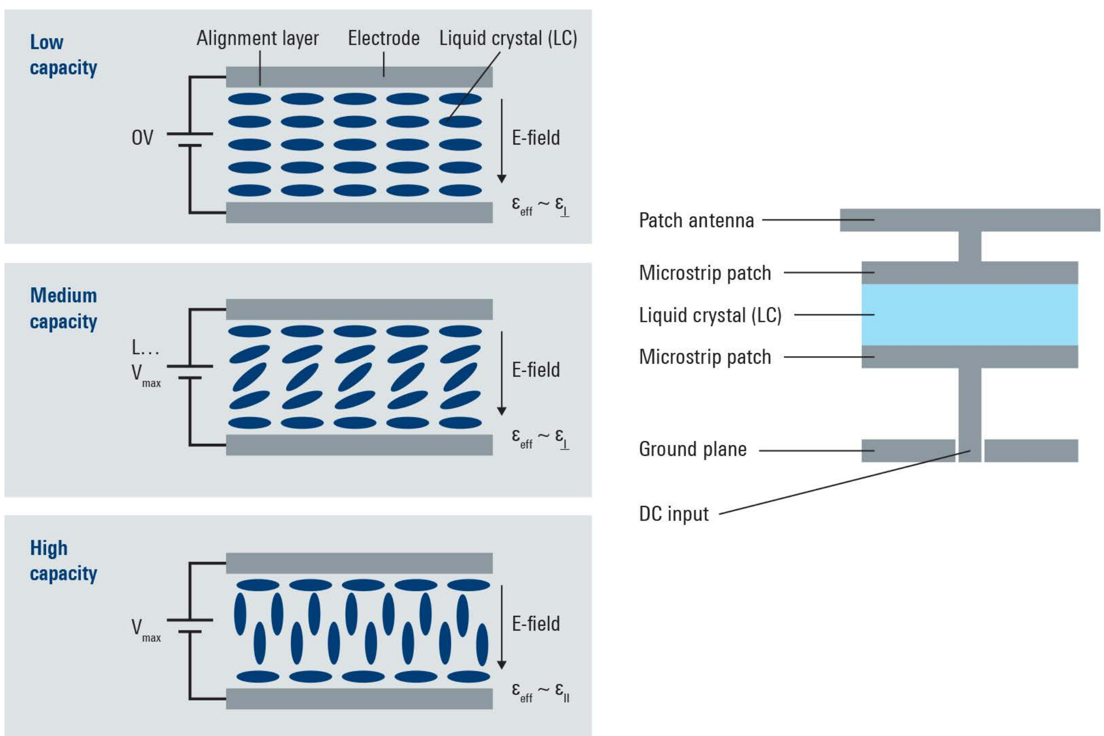
(FR2) and uses liquid crystals. The second type is for signals between 6 and 7 GHz and has conventional, reconfigurable RF components that can be manufactured using PCB technology. In principle, liquid-crystal-based RIS also work with significantly higher frequency signals.

So far, usability up to 100 GHz has been demonstrated. The limiting factor in such a metamaterial concept is the switching time when the electric field is turned off. Liquid crystals have a certain rotational viscosity based on liquid-crystal layer thickness, with a relaxation period before all of the liquid crystals can be arranged parallel to the alignment layer again. Layer thickness of 5 m can take tens of milliseconds, but this switching time is good enough for many practical applications.

Before the project officially ends in 2025, it will also look at specific use cases for RIS, create concepts for network integration, and develop measurement concepts to characterize them. One possibility for the latter is based on a conventional setup with a feed antenna in an anechoic chamber (**Fig. 6**).

Future Prospects for Reconfigurable Intelligent Surfaces

RIS technology is a promising approach to mobile network coverage in the FR2 range and beyond. Further technological development will focus on reducing costs to compete with existing alternatives such as access points and repeaters. After all, use cases for

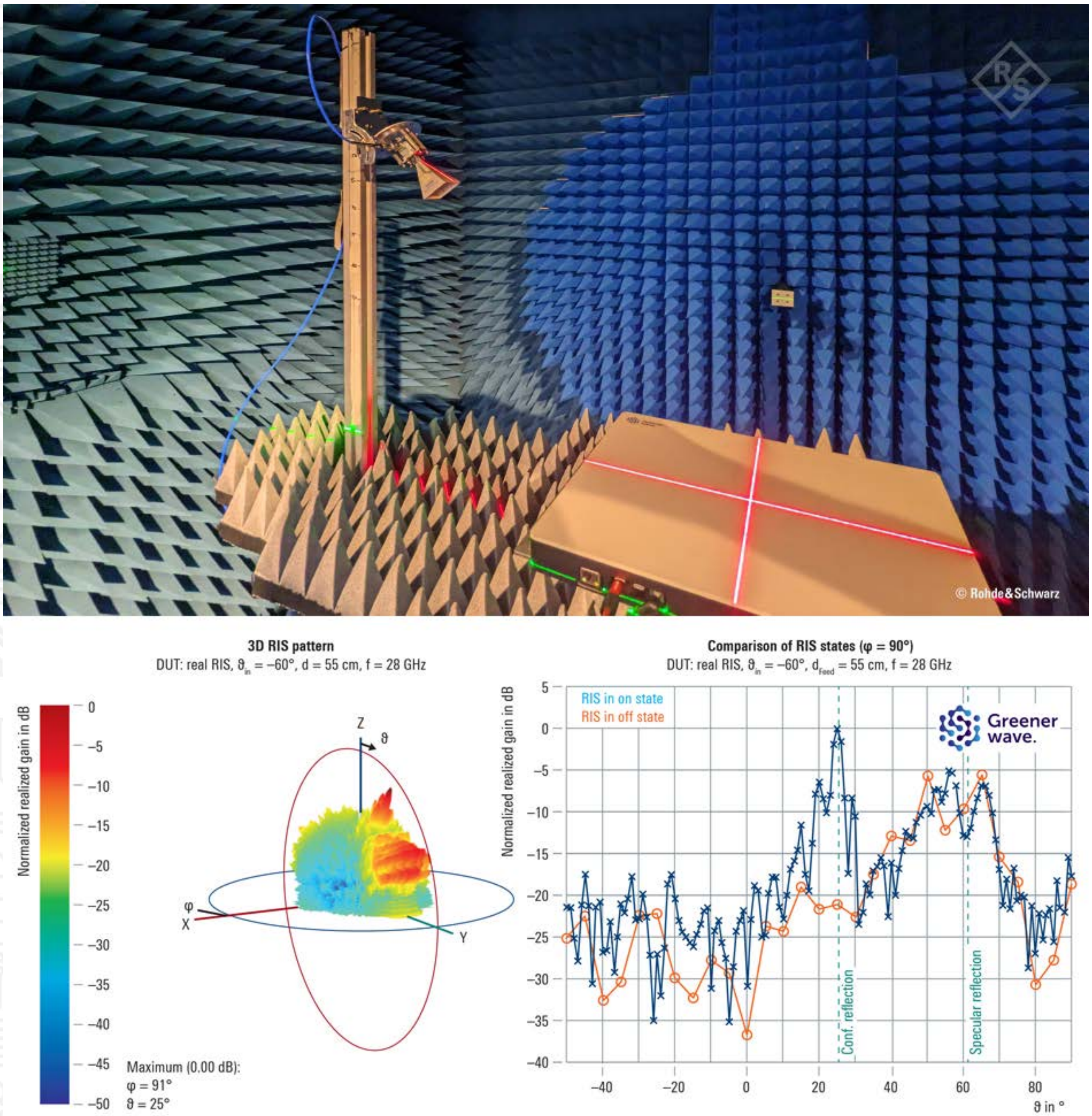


5. Variable plate capacitor with liquid crystals as a dielectric between two glass substrates for RF applications. When no voltage is applied, the top layer (called the orientation layer or alignment layer) stimulates the liquid crystals to align the molecules parallel to the substrate. As the voltage increases, the molecules gradually align themselves vertically and the capacitance C of the capacitor increases (left). How to integrate this component into a (simplified) antenna structure is shown on the right.

network operators also depend on economic factors.

RIS will be used where the benefits of installing them exceed the costs (development and acquisition costs, possibly also rental payments for installation on building facades). The potential is certainly there.

Another interesting use case for Rohde & Schwarz is reconfigurable intelligent surfaces that can change electromagnetic conditions in measuring chambers. This would allow



6. The image on the left shows a test setup for characterizing phased-array antennas in an anechoic chamber, which can also be used in a similar form for RIS. You can see both the device under test (marked with a crosshair) and the feed antenna. The image on the right shows the 3D reflection pattern of a real RIS provided by Greenerwave.

testing teams to create quiet zones in any required shape and size or change channel conditions to suit specific applications. Together with project partners, Rohde & Schwarz continues to explore the potential of liquid crystal in RF applications and drives their commercial use in 6G mobile communications, which will be introduced around 2030.

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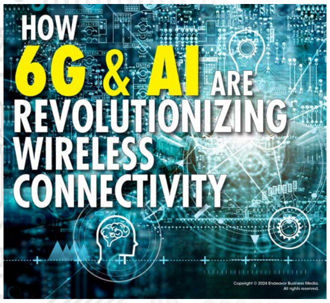
BACK TO TABLE OF CONTENTS



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CHAPTER 2:

The Essential Role of AI in Building 6G's Future

MARIE HATTAR, Senior Vice President, *Keysight Technologies*

6G will be the first generation of wireless to be AI-native. What technologies are in place to make it happen?

The future of wireless is closer than you might think, with 6G networks promising higher performance and flexibility to enable use cases that go far beyond what we do with today's wireless systems. Standards and specifications development has just begun with the first 3rd Generation Partnership Project (3GPP) release, including 6G expected "no later" than March 2029.

Research is beginning its shift to development. We can expect early trials of 6G technologies starting in 2027. 6G research and early development is progressing in tandem with AI maturity, ensuring that 6G will be the first generation of wireless to be AI-native. The technology will be pivotal in realizing 6G's potential for intelligent, autonomous, and transformative wireless communications—opening new possibilities across industries.

A Hyper-Connected World in the 6G Era

6G wireless networks will be able to process unprecedented volumes of data in real-time, along with better latency, security, and reliability. With unrivaled compute and connectivity, traditional on-and-offline boundaries will disappear as virtual, mixed, and augmented reality become part of our lives.

Possibilities include enterprise metaverses where employees teleport to work regardless of their physical location, or haptic sensory suits that remotely control industrial machines and react to scenarios in real-time. The massive amount of data processing and networking that's involved with these and other 6G applications, combined with the ever-increasing complexity of wireless networks, make AI a critical element to 6G's success.

What follows are some of the key ways the technology will support the future of wireless:

Network optimization and automation

Channel-state information (CSI) is used in real-time throughout a wireless system to adapt radio transmissions to current conditions while maintaining optimal performance.

Policymakers are anxious for the new spectrum under consideration for 6G to be shared rather than exclusive. This means sharing with non-cellular systems (radar, satellite, government) and other mobile operators.

Precise CSI is a computational- and resource-intensive task, making it ideal for AI. Algorithms could send the minimum information needed, delivering significant gains in performance, resource utilization, and energy efficiency.

The technology can also enhance channel-state predictions and thus improve beamforming. This would enable more efficient, effective, and reliable management of radio links adjusting to changing environments while consuming fewer resources, supporting sustainability goals.

Solving spectrum-sharing challenges

Policymakers are anxious for the new spectrum under consideration for 6G to be shared rather than be exclusive. This means sharing with non-cellular systems (radar, satellite, government) and other mobile operators, leading to concerns around spectrum utilization, coexistence, and reliability.

AI can address these issues in numerous ways. They include intelligent sensing capabilities to more accurately identify available spectrum and any potential interference, adaptive allocation based on network conditions and user demands, and learning from network data to optimize spectrum-sharing protocols.

Scenario planning to optimize resource allocation

AI can optimize resource allocation based on usage patterns. For example, by analyzing data from a city's commute times versus traffic during midday, the model would predict how much bandwidth is needed at peak times and then shift to other areas after the commute is over. In addition, it can aid traffic management of network data once data messages get into the wired part of the wireless network. This dynamic approach, which is enabled by AI, enhances sustainability goals.

Improved security and resilience

Another benefit of AI-native 6G is enhancing security and resiliency through real-time threat detection, vulnerability management, security analytics, and automated security controls. The intelligence supports context-aware defenses and distributed security at the network edge.

AI is No Silver Bullet

AI is an exciting technology that can solve numerous wireless challenges that plague us today, but it's a fallacy to assume it should be the default tool for every 6G problem. There are some situations where AI's performance is on par—or worse—than traditional methods. In these scenarios, it's not worth developing an algorithm to replace the legacy approach.

Moreover, there are areas where the technology may not make economic sense because it's too power-hungry. That's why it's essential to evaluate every use case and determine if and how to deploy AI.

Evaluating interdependencies is another important step. For example, if AI replaces one element in a system, the training and integration process is straightforward. However, if there are multiple elements, not only is training more complex, but trained systems can "fight" with each other, resulting in suboptimal behavior.

Trustworthiness is another vital consideration. For the industry to rely on the technology, it's critical to understand the pattern AI will follow to arrive at a specific output based on the information provided. Trustworthy AI models must be reliable, work as expected every time, and be explainable.

The Path Ahead for 6G

We are in the early days of learning AI's limits and best practices, but its revolutionary potential impact on wireless communication can't be overstated. AI-powered 6G will bring new applications to every sector, ranging from immersive consumer experiences to high-powered machine-to-machine communication.

Such technologies will continue to work in lockstep together as the industry prepares for this next generation of mobility, creating a future in which communication and connection will know no bounds.

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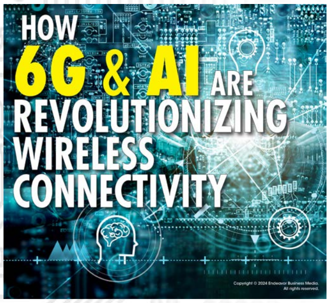
☞ BACK TO TABLE OF CONTENTS



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CHAPTER 3:

How Will mmWave Tech Impact Tomorrow's Telecom Ecosystem?

TUDOR WILLIAMS, Chief Technology Officer, *Filtronic,* https://filtronic.com/

Though advances in 6G technology are still unfolding, the insights gained from achieving high performance and efficiency with 5G provides a roadmap for future innovations.

In an era where the world is still grappling with the potential of 5G, the leap to 6G presents both exciting opportunities and considerable unknowns. While 6G remains largely uncharted territory, the experiences garnered from earlier technological advances provide a strong foundation for overcoming the complexities of this migration.

The next phase of 5G and future 6G include targets of achieving wireless xHaul data rates of 100 Gb/s. Currently, the highest capacity xHaul links operate at around 25 Gb/s.

Although mmWave and E-band, 71 to 86 GHz, have delivered major leaps forward with data rates in excess of 10 Gb/s, a different approach involving multiple mmWave channels will be needed to reach future targets. Therefore, we will likely see the aggregation of different frequency bands, with the next target bands—W and D—pushing beyond the 100-GHz mark.

W- and D-Band frequencies

A clear advantage of W- and D-band frequencies lies in the significantly wider bandwidths they offer compared to lower-frequency bands. This broader spectrum is critical as data demand continues to surge, driven by the proliferation of connected devices and the increasing complexity of data-intensive applications. W-band frequencies—92 to 114.5 GHz—and D-band frequencies—130 to 175 GHz—provide vast, contiguous blocks of spectrum, which are essential for supporting the high data rates required by modern communication networks.

These high-frequency bands are particularly well-suited for xHaul networks, which integrate fronthaul and backhaul connections to create a more efficient and flexible system architecture. By using these bands, networks can achieve lower latency and higher throughput, ensuring a more responsive and reliable user experience.

Specifically, D-band offers even greater bandwidth capabilities, potentially up to 4X that of lower-frequency bands. This expanded capacity is crucial for future-proofing networks against the exponential growth in data traffic.

D-band's ability to handle such high bandwidths facilitates enhanced performance and capacity, which is vital for supporting data-intensive applications such as augmented reality (AR), virtual reality (VR) and the Internet of Things (IoT). These applications demand robust and high-speed connections to function effectively, and D-band's superior bandwidth ensures that network performance remains optimal even under heavy load.

Migration Challenges with W- and D-Bands

These bands are pivotal as they're expected to see the first commercial deployments above 100 GHz, marking a significant milestone in the journey toward ultra-high-frequency communications. Crucially, manufacturing processes for W-band are still compatible with existing methods, albeit pushing the boundaries of current manufacturing tolerances.

Such an alignment allows for a smoother transition into higher-frequency operations without necessitating a complete overhaul of established manufacturing infrastructures. As a result, it accelerates the time-to-market for new technologies in this band.

However, the progression into D-band presents a more complex scenario. Research in this area is advancing well, with available semiconductor processes in indium phosphide (InP) delivering the necessary power for high-frequency operations, though it's currently reliant on costly boutique processes. The cost factor remains a critical hurdle that needs addressing to enable full commercial deployment.

Moreover, integration challenges are more pronounced in D-band. Traditional wire bonds are unfeasible at these frequencies, necessitating the adoption of alternative interconnect technologies such as flip-chip, waveguide interfaces, or hot vias. These technologies are essential not only for performance, but also for their potential scalability in volume manufacturing—a key factor for the commercial viability of telecommunications infrastructure in D-band.

While significant progress in the W- and D-bands outlines these promising short-term and mid-term advances in telecommunications, looking further into the future presents even more complex challenges, particularly when considering the design and manufacturing of devices capable of operating at 300-GHz frequencies.

Non-Terrestrial Needs

On Earth, networks operate within the relatively familiar confines of our atmosphere, where distance limitations are measured in kilometers and power requirements are readily met. In contrast, communication distances in space balloon into thousands of kilometers, necessitating solutions that can punch through the void with greater power while also remaining energy efficient.

Platforms like satellites and balloons become new transmission towers, imposing tight weight and size constraints on the equipment they carry. And the harsh reality of space adds an extra layer of complexity, with components needing to withstand the unforgiving onslaught of radiation. Satellites and high-altitude platforms, which must contend with the formidable constraints of gravity, require components that strike a delicate balance between power and minimal weight.

This imperative for lightweight, yet powerful, components has spurred significant innovation in materials science and engineering. For example, advanced composites and alloys

One of the primary hurdles currently facing manufacturers is the underlying semiconductor technology require to achieve the necessary high frequencies.

are increasingly employed to reduce weight without compromising structural integrity or performance.

Engineers also focus on optimizing the design of these components to ensure they consume less power. The power efficiency not only reduces the size and weight of the power supply units, but also extends the operational lifespan of the satellites and balloons, too.

The move to miniaturization is key here, where the goal is to compress the capabilities of conventional equipment into increasingly compact forms. This involves leveraging advanced materials, designing sophisticated heat-dissipation mechanisms, and employing innovative packaging techniques—all of which are essential in creating components that are both lightweight and highly functional.

As for safeguarding against space radiation, engineers must employ a multilayered defense strategy that goes beyond traditional protection methods. This includes the use of specialized components and shielding materials designed to absorb or deflect high-energy particles.

Such materials are often lightweight yet robust, tailored to add minimal weight while providing maximum protection. In addition, the implementation of redundant circuitry is a key strategy, where multiple copies of essential components are included; if one fails due to radiation, others can take over.

Fault-tolerant designs also play a crucial role. Systems are built to detect and correct errors autonomously, enabling them to continue functioning even when some damage occurs.

Semiconductor Technology for High Frequencies

One of the primary hurdles currently facing manufacturers is the underlying semiconductor technology required to achieve the necessary high frequencies. At these frequencies, semiconductors become a critical focal point in the overall design. Each semiconductor material has unique properties that can support the critical design requirements.

At lower frequencies, a mix of performance and cost often leads to the integration of several individual semiconductors. For higher frequencies, the aim will be to integrate as much of the functionality as possible into a single chip, to minimize interconnects and the related problems outlined above.

It's therefore likely that much of the integration will be in the form of a silicon chip. However, the high-performance elements, such as the power amplifier and LNA, must remain in a compound semiconductor material to maintain the required performance. For W-band, existing semiconductor technologies are being stretched to their limits, but they're still within achievable tolerances. This includes precise placement tolerances, wire bonding, and machining accuracy.

For instance, in W-band applications, maintaining signal integrity requires high precision in component placement and interconnects to ensure minimal signal loss and optimal performance. The D band, though, presents more significant challenges. Currently, commercially viable semiconductor technologies for D-band aren't yet fully developed. While boutique processes are capable of handling D-band frequencies, these aren't suitable for high-volume commercial applications due to their high costs and limited scalability.

This means that widespread adoption of D-band frequencies may still be several years away, pending advances in semiconductor manufacturing technologies. That said, a significant development in Filtronic's mmWave technology involves the use of high-power, solid-state power amplifiers (SSPAs).

Traditionally, the compound semiconductor gallium arsenide (GaAs) has been used within mmWave SSPAs due to its long history and established performance. However, even at higher frequencies, such as those above 40 GHz, gallium nitride (GaN) is now becoming more prevalent. GaN offers better power density and efficiency, allowing for more power output from the same surface area. Not only does that help make devices more compact, but it also extends the range of signal transmission.

While advances in the realm of 6G technology are still unfolding, the insights gained from achieving high performance and efficiency with 5G provide a crucial roadmap for future innovations. Designing solutions for 6G frequencies is conceivable, but achieving scalable production for such high frequencies continues to be an ambitious goal—more a vision for the future than a reality of today.

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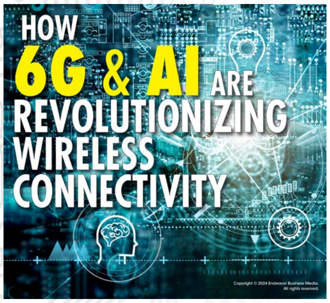
☞ **BACK TO TABLE OF CONTENTS**




Cinch Connectivity Solutions

CHAPTER 4:

Advanced RF Connectors Critical to 6G Network Success

KETAN THAKKAR, Senior Product Manager, *Cinch Connectivity Solutions*
https://www.cinch.com/

As 6G pushes the boundaries of data transmission, RF connectors must evolve to meet the demands of higher frequencies while maintaining signal integrity.

The rise of 6G technology is revolutionizing wireless communication, delivering unprecedented speed, ultra-low latency, and the ability to operate at frequencies well into the terahertz range. These advances bring vast potential for next-generation applications, but they also introduce significant technical challenges for RF connectors, which are crucial in ensuring reliable signal transmission.

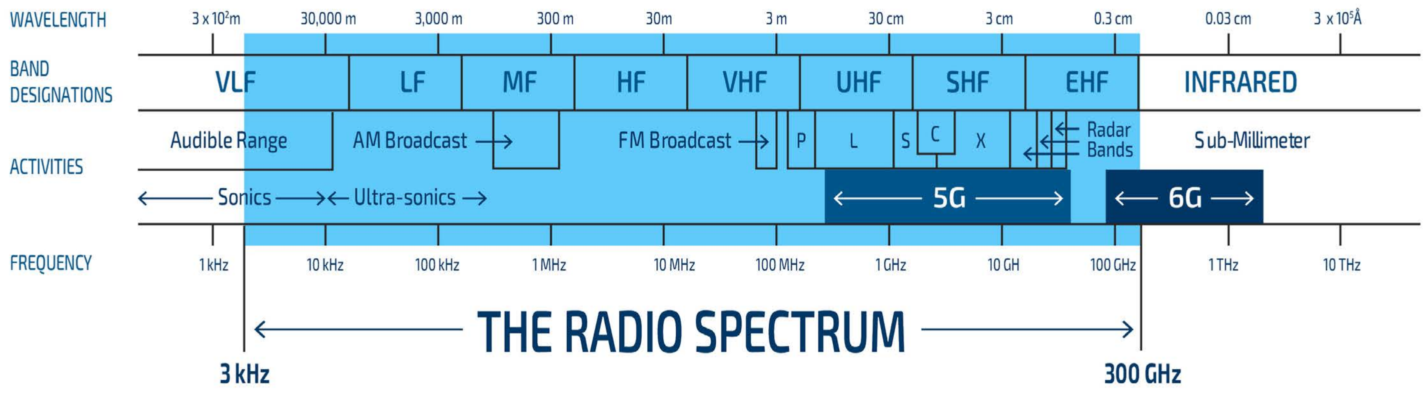
As 6G pushes the boundaries of data transmission, RF connectors must evolve to meet the demands of higher frequencies while maintaining signal integrity. This article delves into the impact of 6G on RF connector design, exploring the need for advanced materials, improved shielding, and precision engineering to address critical issues such as insertion loss, return loss, and phase stability. It also examines future trends, evolving standards, and testing protocols that will shape the future of 6G-enabled wireless infrastructure.

The Promise of 6G

6G technology, the next evolutionary leap in wireless communication, promises to dramatically outperform 5G in speed, latency, and network capacity. With peak data rates expected to surpass 100 Gb/s and latency reduced to near-zero, 6G will enable a new era of applications. These will include real-time holographic communication, autonomous systems, and advanced augmented reality experiences.

Central to the success of these networks will be the RF connectors, critical components that link cables, antennas, and devices, ensuring reliable signal transmission throughout the communication system.

While 5G networks continue to proliferate, the rise of 6G introduces new complexities in RF connector design. In 6G, the transition to terahertz (THz) frequencies—well beyond 100 GHz—demands that RF connectors evolve to address higher frequencies, more com-



1. The transition to terahertz frequencies demands that RF connectors evolve to address higher frequencies.

Cinch Connectivity Solutions

pact designs, and new signal integrity challenges (**Fig. 1**).

RF connectors operating efficiently in 4G and 5G networks face significant limitations in 6G environments, where smaller wavelengths and higher-frequency signals present challenges in managing power, precision, and durability. These connectors must become more than passive components—they must be active contributors to ensuring the success of 6G networks.

As the 6G ecosystem grows, engineers and designers are faced with rethinking RF connector design to meet the stringent requirements of terahertz-frequency operations. Innovations in materials, shielding, and precision engineering are essential to maintaining signal integrity at these higher frequencies. Without these advances, the promise of 6G technology will remain unfulfilled, as the quality of data transmission depends heavily on the performance of RF connectors.

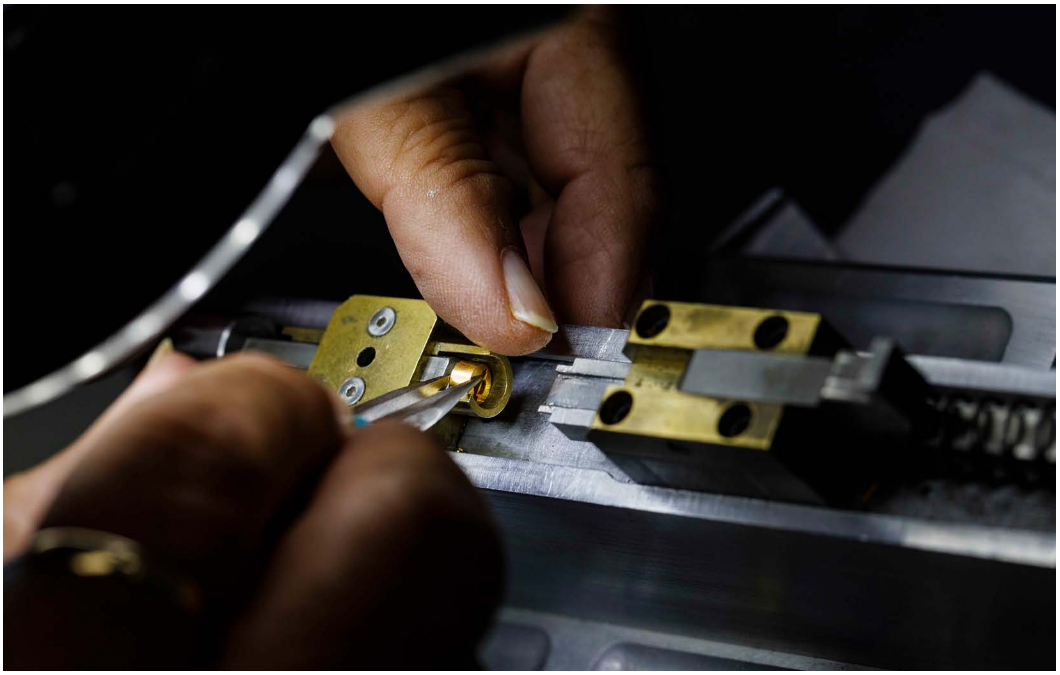
Technical Challenges for RF Connectors in 6G

The transition to 6G presents several technical challenges for RF connectors, many of which stem from the physics of operating at frequencies above 100 GHz. At these frequencies, signal wavelengths become much shorter, which introduces significant difficulties in maintaining signal integrity, managing power loss, and ensuring precision.

One of the most pressing challenges is insertion loss, which refers to the loss of signal power as it passes through a connector. As the signal frequency increases, insertion loss becomes more pronounced, and this degradation can negatively impact system performance.

The relationship between insertion loss and frequency is nonlinear, meaning that RF connectors performing well at 20 GHz may suffer significant degradation when operating at frequencies above 100 GHz. This problem is exacerbated by higher frequencies and increasing attenuation and dispersion, making it even more difficult to maintain signal quality.

Another critical issue is return loss, which occurs when a portion of the signal is reflected to the source due to impedance mismatches in the connector. Even slight imperfections in connector geometry can cause significant signal reflection at terahertz frequencies (**Fig. 2**). This wastes power and introduces phase errors, which can distort the transmitted signal. Ensuring proper impedance matching becomes a critical aspect of RF connector design as the signal becomes more sensitive to even minor imperfections.



2. Even slight imperfections in connector geometry can cause significant signal reflection at terahertz frequencies. Cinch Connectivity Solutions

Phase stability is another significant challenge, especially at higher frequencies. Precise signal timing is crucial in advanced communication systems, but maintaining phase stability becomes increasingly difficult at terahertz frequencies. Small changes in the connector's characteristics—caused by environmental factors such as temperature fluctuations or mechanical stress—can result in phase distortion. This, in turn, may degrade overall system performance, impacting the reliability and speed of 6G networks.

Technological Advances in RF Connector Design

To meet the rigorous demands of 6G technology, engineers are focusing on several key areas of innovation in RF connector design. One of the most critical areas is materials science. As power dissipation increases at higher frequencies, connectors must be made from materials that offer excellent thermal management without compromising mechanical stability.

High-performance materials such as beryllium copper, advanced ceramics, and other conductive alloys are being explored for their ability to minimize resistive losses and enhance the durability of connectors operating at terahertz frequencies. These materials also need to offer sufficient strength to withstand the mechanical stresses induced by high-frequency signal transmission.

Shielding is another area where significant strides are being made. At terahertz frequencies, electromagnetic interference (EMI) threatens signal integrity more. External noise can easily disrupt signals without adequate shielding, leading to serious performance degradation.

Engineers are developing advanced shielding techniques that include multilayer coatings and innovative geometric structures to minimize signal leakage and reduce susceptibility to interference. These techniques are vital to maintaining signal quality and ensuring that the RF connectors can operate efficiently even in challenging environments.

In addition, precision engineering plays a critical role in addressing the challenges of 6G. As devices become smaller and more integrated, RF connectors must also shrink down without sacrificing performance.

This requires manufacturing processes that can achieve submicron precision, allowing for the creation of connectors that maintain optimal impedance matching and minimal signal reflection at frequencies exceeding 100 GHz. Micromachining techniques and advanced 3D modeling and simulation tools enable engineers to design connectors that meet the stringent demands of 6G systems.

Evolving Standards and Testing for 6G Connectors

As 6G technology evolves, new standards for RF components are being developed to account for the unique challenges of operating at terahertz frequencies. These standards will address electrical performance metrics (e.g., insertion loss, return loss, phase stability) and environmental factors (e.g., robustness against temperature extremes, vibration, and moisture). RF connectors in 6G systems must be able to perform reliably in a wide range of conditions, from outdoor installations to mission-critical environments.

Testing protocols are being developed to ensure that RF connectors meet the rigorous demands of 6G networks. Traditional testing methods, which were sufficient for 4G and 5G networks, are no longer adequate for evaluating performance at terahertz frequencies.

New testing techniques include high-frequency S-parameter measurements, time-domain reflectometry, and environmental simulations designed to replicate real-world operating conditions. These tests are essential for verifying that connectors can maintain performance in the face of the demanding conditions presented by 6G technology.

Future Trends in RF Connectors for 6G

Several key trends are expected to shape the future of RF connector design as 6G technology continues to develop. One of the most prominent trends is the ongoing drive toward miniaturization.

As mentioned, as devices become smaller and more compact, RF connectors will need to fit into increasingly limited spaces without compromising performance. Achieving high-frequency performance in such small form factors will require even greater precision in manufacturing processes and materials.

Another emerging trend is the exploration of RF-optical hybrid solutions. These systems combine traditional RF connectivity with optical transmission, offering the potential to overcome some of the limitations of purely electrical connectors at terahertz frequencies. By incorporating optical technology, hybrid solutions could lead to lower insertion loss and higher band-

3. Engineers are developing new RF connectors to ensure the long-term reliability of 6G networks.
Cinch Connectivity Solutions

widths, making them a promising solution for 6G networks where high data rates and signal integrity are paramount.

Durability is also becoming an increasingly important consideration in RF connector design, particularly for connectors that will be used in harsh environments. Outdoor installations, mission-critical applications, and high-stress environments require connectors that maintain consistent performance over time, despite extreme temperatures, moisture, and mechanical vibration exposure. Engineers are developing new materials and designs that will enable RF connectors to withstand these challenges while ensuring the long-term reliability of 6G networks (**Fig. 3**).

What Comes Next for RF Connectors?

As 6G technology continues to push the boundaries of wireless communication, RF connectors will play a pivotal role in ensuring the performance and reliability of next-generation networks. The shift to terahertz frequencies presents significant technical challenges, including increased insertion loss, return loss, and phase stability issues.

However, through advances in materials, shielding, and precision engineering, RF connectors are evolving to meet those demands. At the same time, evolving standards and rigorous testing protocols are being developed to ensure that RF connectors can handle the unique challenges posed by 6G technology. By overcoming these technical hurdles, RF connectors will enable the full potential of 6G, supporting the transformative impact this technology will have on industries and society.

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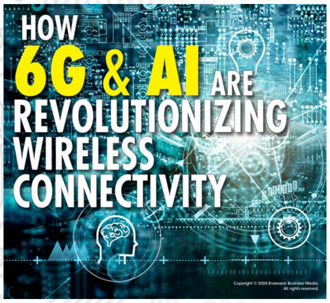
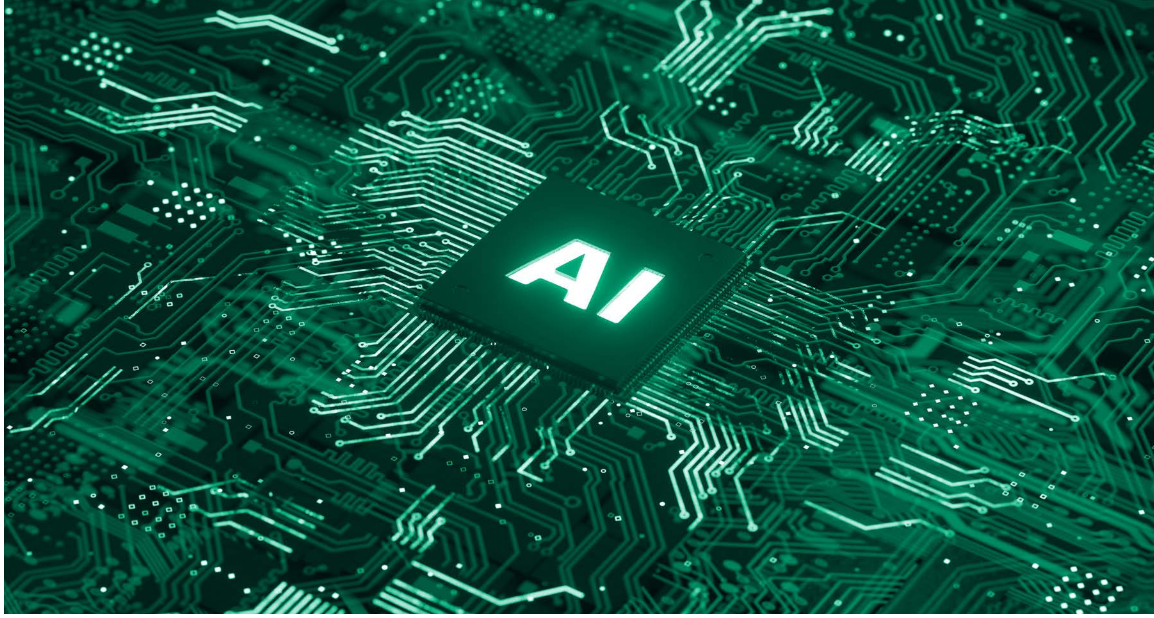
☞ **BACK TO TABLE OF CONTENTS**





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CHAPTER 5:

What's Trending in 6G Research and Business?

SARAH LASELVA, Chief Product Marketing Manager, RF & Wireless,
Emerson Test and Measurement

Now is a good time to reflect on the current research and economic trends that need to be addressed to make 6G a success.

The typical development cycle for a cellular generation is 10 years. With the first 6G technology deployments slated for 2030, that puts us roughly halfway through the development cycle as 2024 comes to an end and 2025 kicks off. Although it will be another two to three years before the first 3GPP standard for 6G is finished, this is a good time to reflect on the current research and economic trends that must be addressed to make 6G a success.

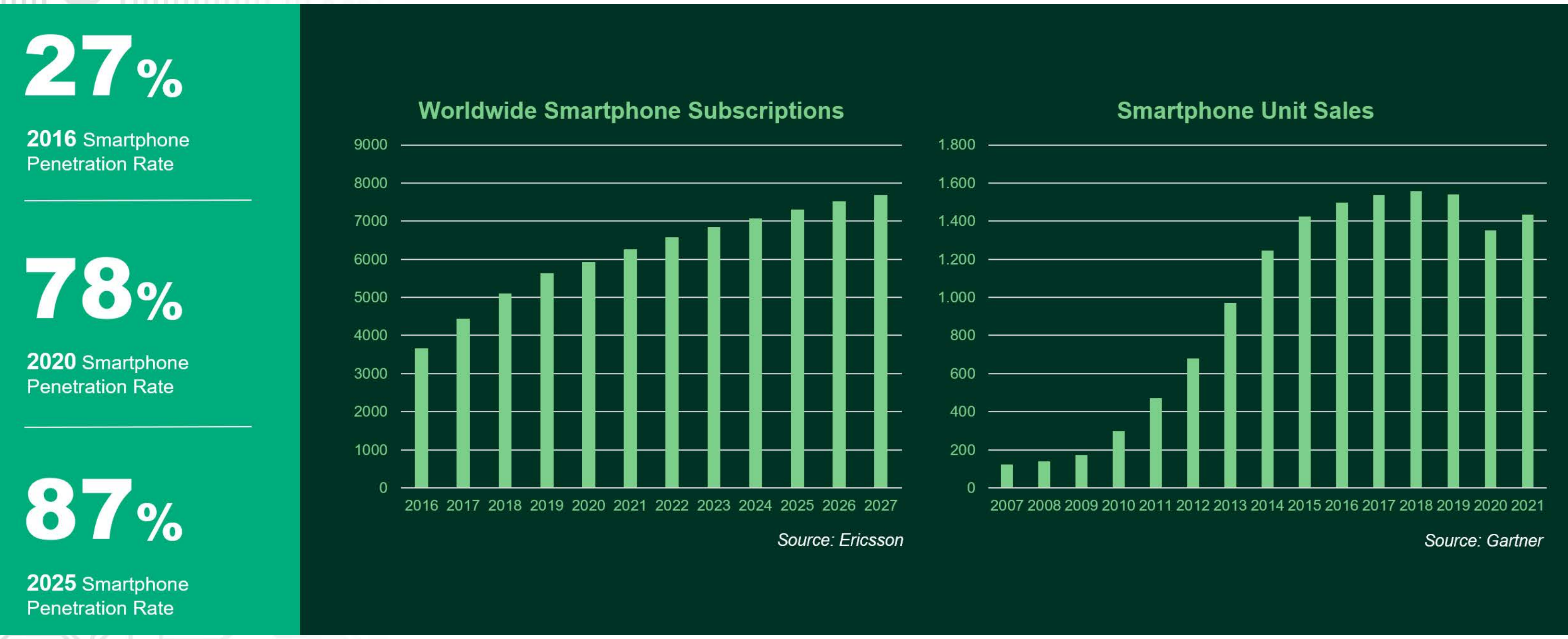
6G Business Trends

For 6G, considering the current economic state adds clarity to why some technologies and applications are being prioritized over others. In the past four years, there was a global pandemic, multiple wars, disrupted supply chains, and an ever-present threat of recession. Economic uncertainty paired with large investments made into 5G infrastructure have created a financially conservative atmosphere for 6G development.

The cellular industry is experiencing a shift from a growth market model to a profitability model. The number of consumer cellular subscriptions is beginning to plateau (**Fig. 1**). Consumers are also keeping their devices longer.

These two market forces combined are forcing the information and communications technology (ICT) industry to evaluate new business models (for example, the concept of creating application programing interfaces to run on top of the network). Simultaneously, there's a push to make networks as efficient as possible to lower operational expenses.

5G uses less power per bit than 4G, but the number of bits being transmitted today is exponentially higher than it was 10 years ago. Techniques for power reduction are being used in 5G, and 6G has an opportunity to natively adopt them and implement other improvements. This will make 6G networks cheaper to operate long term while addressing



1. The cellular industry is experiencing a shift from a growth market model to a profitability model as the number of consumer cellular subscriptions begins to plateau. Emerson Test & Measurement

global Net Zero and sustainability goals.

Even if the desire to invest in new infrastructure from telcos is tempered, there's still a clear need for 6G. The demand for cellular services continues to grow and those demands can't be met with existing technology alone. Lessons from 5G will help 6G, too, like not having multiple split options and skipping non-standalone and moving straight to standalone.

In parallel, AI and quantum computing are maturing. Both technologies represent a threat to the security of current cellular technology. AI also represents a once-in-a-generation opportunity for innovation.

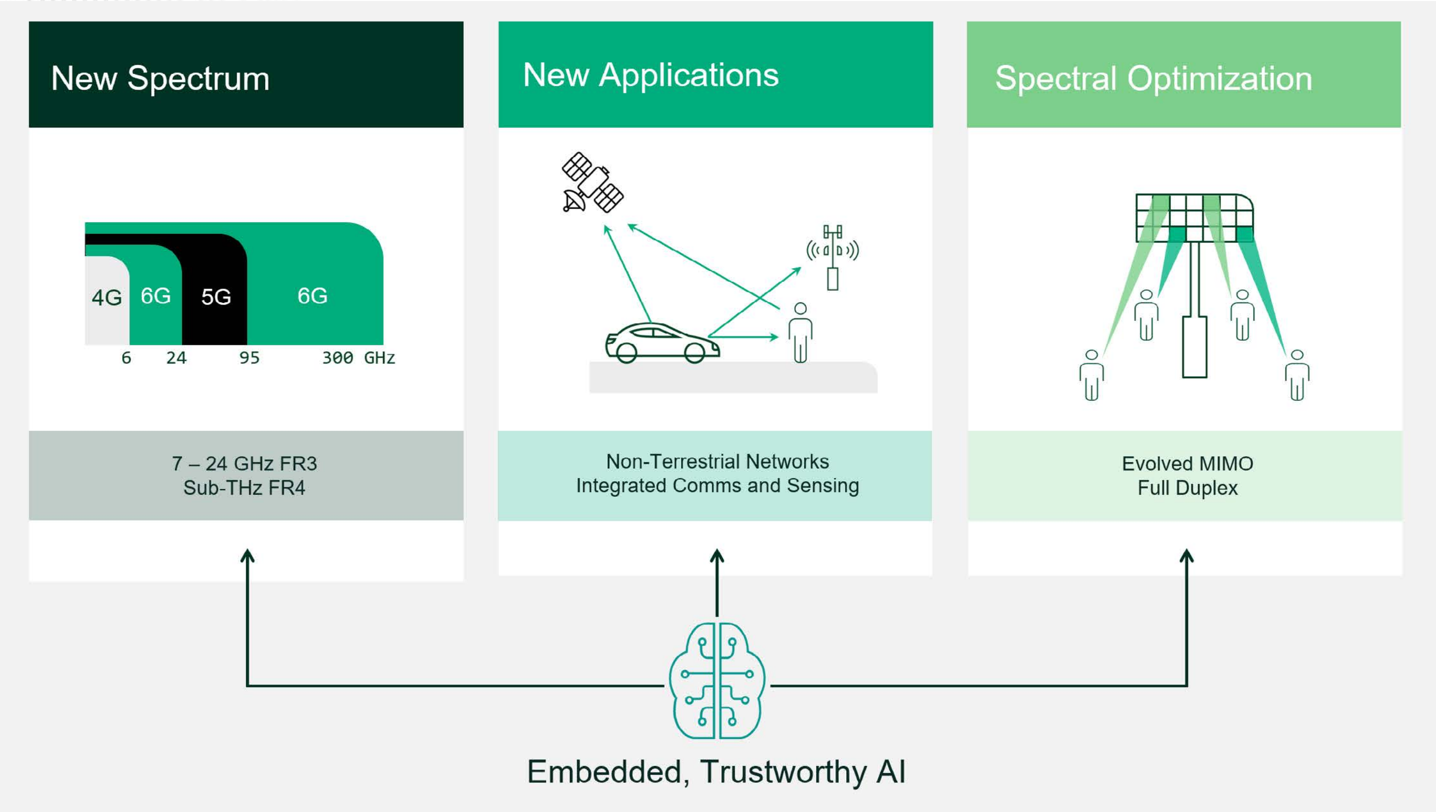
With all of this in mind, it seems likely that 6G will be a technological evolution, leveraging the massive improvements to the infrastructure and protocol stack that were started in 5G. And as that core technology matures, it can serve as the foundation to revolutionize the applications and use cases for cellular technology.

Technology Trends: From Massive MIMO to O-RAN

At the heart of 6G is spectrum expansion (**Fig. 2**). New spectrum is required to increase capacity, and the most promising bands for 6G are between 7 and 24 GHz (or "FR3" or the upper-mid band). The 7- to 15-GHz band has preferable propagation characteristics—it's the spectrum that the ICT industry is pushing to be earmarked for licensed cellular transmission. There are many incumbents across this spectrum and regulatory challenges must be addressed.

Sharing spectrum is a proposed way to help alleviate some of these challenges, but sharing spectrum historically has been less than ideal. With advances in AI, which is uniquely well-suited to optimizing complex systems like wireless networks, new solutions for spectral sharing in 6G hold promise.

MIMO improvements have played a significant role in every 3GPP release since release 15, and this trend will continue. Moving into slightly higher bands makes it possible for massive MIMO to evolve thanks to smaller antenna sizes. The ability to add more antenna



2. At the heart of 6G is spectrum expansion to increase capacity.

Emerson Test & Measurement

elements to MIMO systems without dramatically increasing their size is another way that spectral efficiency is being addressed.

The trend to make networks more disaggregated, open, and software-defined is expected to continue into 6G. While O-RAN has had lackluster success to this point, it's far from being a failure. With current geopolitical tensions, O-RAN is a public policy priority for the United States. That pressure will allow for further investment and evolution for open RAN architectures.

Another reason why the move toward O-RAN is important is because it enables innovation. Being able to develop apps to run in the RAN intelligent controller (RIC), for example, gives engineers a way to contribute to the stack outside of 3GPP, which is valuable for small companies and academic researchers who don't have the resources to participate in the standards.

Non-Terrestrial Networks

6G hopes to address numerous applications, but two have significant traction within the industry: non-terrestrial networks (NTNs) and joint communications and sensing (JCAS, or integrated sensing and communications, ISAC).

Using satellites to deliver connectivity is a promising way to deliver global coverage on a scale that's long been desired but impractical. The price point to build and launch a satellite has decreased significantly in the last five years. But whether the business case will have long-term success is yet to be seen. In 3GPP, there's an effort to look at standardizing waveforms and ways to handle mobility.

New channel models are also being built to consider a 3D channel for signals that may be coming from space. The new channel models are also important for sensing applications to account for backscatter and features of sensing waveforms, like radar.

The ability to gain information about the physical world through the communications channel can help in applications like autonomous driving, manufacturing, and gesture recognition. How JCAS will ultimately be used is still to be seen, but adding sensing capabilities to wireless networks is a way to increase networks' value.

The Omnipresence of AI

Underlying all of the technical advances driving 6G is AI. As mentioned, it can optimize complex wireless networks in ways that aren't possible with humans. Research is ongoing into how AI can be used for everything from improving energy efficiency to waveform recognition to channel-state-information (CSI) improvements. 3GPP is actively working to build a framework so that AI can be added into cellular standards, but many challenges remain.

AI is already being used in some areas, but many potential use cases for AI need further research before they will be ready. Before AI models can ever be implemented, they need to be trained. Access to training data for cellular applications is limited. Carriers do have data, but for many reasons, including customer privacy, the data will not be shared (or perhaps it will at a steep cost).

Questions remain in terms of how much training data is needed as well as how often models must be retrained. Researchers are actively working to understand these factors. After training, AI models must be hardened and proven to work reliably, predictively, and better before replacing traditional methods. Testing AI models inside of full-stack real-time networks is a crucial yet difficult step that's needed to evaluate this kind of performance. Limited testing is happening, but much more is required.

AI has been touted to improve the energy efficiency of wireless networks. However, AI today is power-hungry. Thus, adding any AI models into a wireless network comes with a risk of using more total energy than making no changes at all.

AI is rapidly maturing, and so is GPU technology. It's likely that, in the future, the energy efficiency of AI usage will improve. Until that time, the wireless industry needs to better understand the energy tradeoff between using traditional methods and AI. As of now, there's no industry standard way to measure this tradeoff. Some ideas and methodologies have been proposed, but they require more work.

The wireless industry needs a way to deterministically measure and compare the energy usage of AI-enhanced and traditional networks. Research on this topic has begun and will likely improve over the next year or two.

Overall, AI is fundamentally changing how compute power can be used, and the ICT industry is looking to harness this new power. The first 3GPP release to incorporate 6G study items will start in mid-2025, adding more clarity to what technology will be in or out for the initial 6G roll out. The timing for 6G will enable it to capitalize on the power of AI. It could very well be the most efficient and sustainable cellular generation yet. And with any luck, it will unlock new opportunities for humanity to connect and interact with each other.

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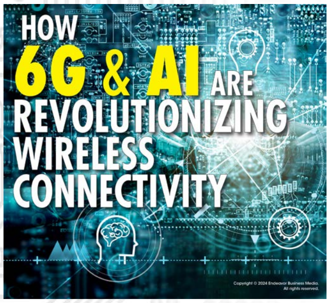
☞ **BACK TO TABLE OF CONTENTS**



Fujitsu

CHAPTER 6:

Charting a More Sustainable Path to 6G

ROB HUGHES, Head of Wireless Solutions Marketing, *Fujitsu*

As we approach the 6G era, the telecom landscape is set to undergo transformative changes. With the promise of ultra-high data rates, ultra-low latency, and ubiquitous coverage for many more devices, 6G will redefine connectivity, empowering innovative new capabilities and immersive use cases. Indeed, expectations for 6G are already high, with visions of holographic and virtual-reality (VR) functions, 3D touch, advances in robotics, and more immersive digital replication.

With the promise of ultra-high data rates, ultra-low latency, and ubiquitous coverage for many more devices, 6G will redefine connectivity, empowering innovative new capabilities and immersive use cases.

Yet, the ability to fully realize these capabilities will place much greater demands on networking infrastructure, requiring massive connectivity, performance, and power. What can we expect this network evolution to look like? And considering the resources required, how can the industry chart an economical and environmentally conscious pathway to 6G?

Lay the 6G Groundwork in the Cloud

Without a doubt, the technology transformation from today's 5G mobile network will require some heavy lifting to enable tomorrow's 6G vision. The course of this evolution includes technological advances, new deployment approaches, the adoption of new radio-frequency (RF) bands, and more economic use of existing spectrum.

Fundamental areas of focus for mobile network operators (MNOs) to achieve this transition successfully will involve increased flexibility, efficiency, and innovation in the way that networks are designed and deployed.

Fueling this ongoing evolution to more agile, flexible networks is increasing reliance on virtualized, cloud-native infrastructure, which is driving a paradigm shift in mobile network technology. Due to this virtualization, compute functions now reside across the network, requiring the ability to respond quickly to real-time demands wherever needed, whether at the edge of the network or the core.

To facilitate this dynamic allocation of resources, radio-access-network (RAN) architec-

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ture will require even greater automation, ability, and intelligence. In fact, increasing reliance on artificial intelligence (AI) and machine learning (ML) will be a necessity to manage and optimize network performance for ultra-high data rates.

Advanced AI/ML functions will allow for network conditions and user behavior to be analyzed in real-time. This, in turn, will enable dynamic network management, resource allocation, and optimized data flow to support varying types of use cases for outstanding quality of experience (QoE) all the way to the network's edge.

Allocate the Right Radio Resources

In addition to the changing location of compute functions in the network, the location and operation of base-station radio units (RUs) will also need to be modified to support the ultra-high data rates expected with 6G. Specifically, MNOs must selectively use high-frequency bands that offer significantly higher bandwidths compared to lower 5G frequencies, particularly those in the millimeter-wave (7 to 24 GHz) and sub-terahertz (100 to 300 GHz) ranges.

The use of higher frequencies with shorter signal attenuation and limited building penetration capabilities will reduce 6G cell radius, requiring radios to be located closer to subscriber devices. Operating at these frequencies also introduces path loss, limiting spectrum utilization efficiency.

As a result, new higher frequencies are expected to be deployed selectively in locations where their high capacity can be fully used, such as ultra-high-density environments and enterprise settings. Other lower-frequency bands will complement high-frequency deployments to offer broader coverage.

Likewise, advanced antenna technologies and new techniques will need to be developed to enhance signal-propagation issues. For example, dynamic spectrum-sharing techniques will be required to enable more flexible and efficient use of available spectrum, which is critical for achieving ultra-high data rates.

By leveraging advanced AI/ML algorithms, 6G networks will predict network congestion and allocate resources accordingly. This will enable dynamic allocation of spectrum resources based on real-time demand and network conditions to optimize data-transfer rates and reduce congestion.

Massively Advanced Antenna Design

Furthermore, massive multiple-input multiple-output (mMIMO) technology will continue to play a crucial role in achieving ultra-high data rates. Advances in mMIMO beamforming techniques will further enhance signal quality, minimize energy waste, and complement the development of more compact and energy-efficient antenna arrays.

Yet, although advanced mMIMO beamforming techniques can help improve capacity, latency, coverage, and energy efficiency, implementing mMIMO in the lowest frequency bands often presents challenges. With the need for additional antenna elements, mMIMO antennas tend to be larger and more cumbersome than traditional macrocell radios, complicating deployment where space is limited. This is particularly true for lower-frequency mMIMO antennas, due to the longer wavelengths of low-band frequencies.

Because mMIMO antennas for higher-frequency bands accommodate shorter wavelengths, they're smaller and more compact, making them well-suited to shorter-range applications for hot spots. Thus, to meet the expected demand for desirable 6G applications, MNOs will need to continue to deploy traditional, non-mMIMO antenna technology for broad coverage, blended with higher-frequency mMIMO antennas to provide high capacity in dense environments.

To address these deployment challenges, the industry is exploring development of advanced antenna designs, such as non-uniform linear arrays (NULAs). This approach involves the use of non-uniform spacing between antenna elements, helping to reduce the overall size and cost of the antenna array while maintaining its performance.

Chart a Sustainable Course

Even before we see 6G networks go live, 5G networks are already driving more power-hungry data traffic, and network demand will only escalate with higher speeds and new applications. It's estimated that the telecom industry consumes approximately 2% to 3% of worldwide energy use, with RAN operations accounting for more than 80% of overall mobile network power consumption.

While increasing network intelligence is already contributing to some energy-efficiency improvements, such as AI-enabled power-savings capabilities, additional measures will be needed for telecom operators to achieve their stated goal of achieving Net Zero between 2030 and 2050.

Fortunately, the transition to next-generation mobile technology offers the potential to usher in a more environmentally friendly technological landscape. One primary objective of 6G is to enhance energy efficiency of network operations, thereby reducing the power consumption of telecommunications infrastructure. Moreover, a focus on environmentally conscious manufacturing processes will further reduce the overall carbon footprint of network equipment and operations.

Due to similarities between the 5G and 6G air interfaces, many existing 5G RUs are sufficiently programmable to accommodate 6G software upgrades. This allows MNOs to continue using existing 5G hardware and avoid the environmental impact of manufacturing new radios.

In addition, network components capable of supporting multiple radio-access-technology (RAT) functionality can optimize radio access selection and compute offload locations based on energy efficiency. It helps minimize environmental impact of the network without affecting performance and reliability.

The ability to leverage software upgrades to enable 6G functionalities will also allow new AI-powered features, including dynamic cell shaping, to optimize the coverage and capacity of the network based on real-time conditions. Similarly, spectrum-sharing techniques such as multi-RAT spectrum sharing (MRSS) will allow for MNOs to further improve network efficiency and capacity through software updates.

Ultimately, 5G radios designed to be software-upgradable to support 6G functionalities will let MNOs extend the lifespan of their current investments. This not only enables return on investment over a longer period of time, but also reduces the need for new hardware and minimizes electronic waste, promoting an economical, environmentally conscious and efficient transition to 6G.

To the Next "G" and Beyond

With the promise of massive connectivity, revolutionary capabilities, and an increasingly digitalized future, the 6G era will transform how we interact with mobile technology. This transition will necessitate a balanced approach that leverages existing infrastructure, while incorporating innovative RF technologies to meet future demands.

By combining spectrum in use today with strategic deployment of high-frequency spectrum, as well as implementing advanced technologies through software upgrades, we can chart a more sustainable path forward to tomorrow's telecommunications landscape.

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☞ **BACK TO TABLE OF CONTENTS**