Next-Generation Wireless: A Guide to the Fundamentals of 6G

KEYSIGHT

An Introduction to 6G

With the deployment of 5G well underway, vendors and service providers can help consumers, industry, and government unleash a multitude of use cases with far-reaching benefits. However, 6G goes much further. 6G technologies will provide unprecedented performance, reliability, and security, fully connecting society for the first time.

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Vision

Physical and cognitive augmentation will make humans far more efficient and productive than they are today. The ubiquitous nature of 6G will enable new industries and business models. By fully connecting the physical, digital, and human worlds, 6G will help us manage the opportunities and challenges of growth and sustainability.

Part of the 6G vision is to support and enable the United Nations Sustainable Development Goals. These goals promote global health, education, quality of life, justice, and inclusion by creating ubiquitous wireless intelligence. A wide range of technologies, such as artificial intelligence (AI), advanced sensors, optics, cloud computing, high-speed digital, satellite, and robotics, will rapidly advance in the next decade, enabling new use models made possible by 6G.

In communications, 6G will enable multisensory technologies to create new ways for people to interact with each other and their surroundings, using not just sight and sound but also touch, smell, and taste. 6G will likely eliminate the physical and temporal distance between people through holographic imaging, seamlessly connecting human-to-human and human-to-machine worlds.

AI will power networks, allowing fully automated infrastructure optimization and autonomous service provisioning. The use of digital twins, exact real-time replicas of physical processes, will be widespread. These virtual models combine past and present data with machine learning to dynamically monitor, improve, optimize, and enhance many processes. Technologies employing precise timing and data orchestration will transform manufacturing and industrial processes as well as the networks that serve them. The environment in which all-inclusive communications will be available will extend to land, sea, air, and space. Finally, 6G will significantly improve society's ability to respond to and manage emergencies whenever they arise.

These are some 6G technology and use case examples, and this eBook briefly introduces each topic. While not all of these examples will come to fruition in 6G, they will drive new technology that will benefit humanity for decades, providing connected intelligence, global coverage, digital inclusion, and the assurance of health and safety.

6G KPIs

- Peak Throughput (1Tbps)
- U-Plane Latency (0.1ms)
- Reliability (nine 9's)
- Connection Density (100/sq m)
- Location Precision (±1cm)
- Battery Life (infinite)
- Energy Efficiency (+1000%)

"Conservative"
Ambitious
5G

Figure 1. Spider diagram comparing 5G and 6G KPIs

KPIs and goals

Each generation of cellular communications introduces updated key performance indicators (KPIs). Figure 1 shows a comparison of 6G KPIs versus 5G KPIs. Given the early stage of 6G, there are two lines: a conservative goal and an ambitious goal. Both sets of goals offer a marked improvement over the performance of 5G.
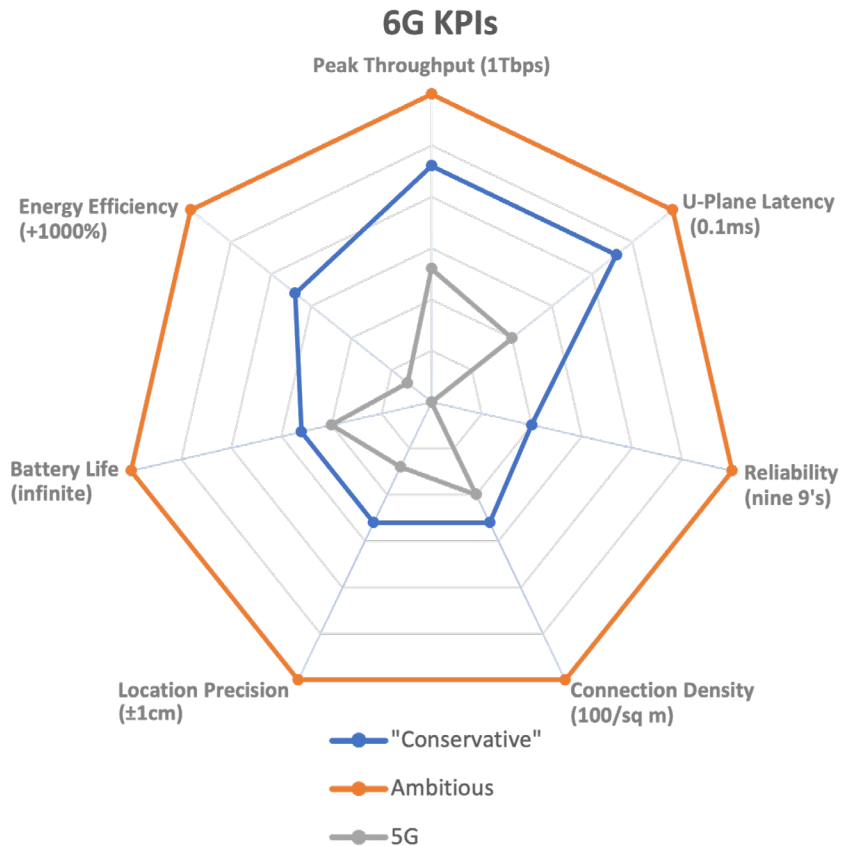
A spider diagram of KPIs does not provide the full picture of 6G's aims. The smart device trend will continue. The 2010s saw the rise of wireless chips integrated into everyday items, including e-readers, fitness trackers, water meters, and kitchen appliances. In the 2020s, this trend will continue and scale. The 6G future is full of smart devices, machines, and robots. 5G initiated autonomous vehicles, and 6G will build on that work, unleashing semiautonomous and fully autonomous machines into the world on a massive scale. Advancements in this area will fundamentally change the way humans interact with machines and how machines interact with the physical world.

6G requires engineers to address technological and ethical problems in new ways. The risk of introducing social biases into the wireless ecosystem is real and could have damaging consequences, such as unequal access to wireless communications. But 6G aspires to improve the quality of human life.

Creating a futuristic cyber-physical world is not the only way 6G looks to better humanity. Sustainability advancements will improve the quality of human life. Creating a greener and less wasteful wireless ecosystem is a top priority for 6G and has already gained significant industry support. Areas of focus include the following:

- Reducing the amount of power required to run networks

- Reducing the amount of power devices consume

- Reducing the emissions resulting from the creation of new devices and equipment

- Improving device recycling

6G Use Cases

As operators worldwide continue to deploy 5G, the next generation of wireless communications technology is in the works. It aims to fill the gaps left by the previous standard and keep up with emerging technologies and trends in the consumer, industrial, and global sectors. While the Third Generation Partnership Project (3GPP) has not defined 6G, major research organizations, network equipment manufacturers, and operators have started building their wish lists for the features, key performance indicators (KPIs), and goals for 6G.

5G focused on advancements in three major areas: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine-type communication (mMTC). 6G will reach beyond those pillars. It will work toward a more holistic, immersive communication fabric, with the flexibility to scale and vary network needs to reach a variety of performance targets, all while working to reduce costs, maintenance overheads, and service times.

Across the 6G ecosystem, various KPIs are rising to the top as the bar is set for the next generation of cellular communications. Data rates, currently in the single-gigabit-per-second range, will have to reach hundreds of gigabits per second, if not 1,000 Gbps, to make significant improvements. Coverage must be available in all parts of the world. It must scale across dense urban areas and rural regions with cost-effective infrastructure or use non-terrestrial networks to close coverage gaps.

Traffic capacity must increase to handle the density of devices, especially as users adopt data-hungry devices like augmented reality electronics and positioning accuracy must increase and detect sub-centimeter distances to accurately beamform to users or deploy sensing capabilities in networks.

Beyond the strictly technical metrics is a need for improvements to make cellular communications sustainable at the business and global community levels. Intelligent communications must maintain bare-minimum coverage, reduce network load, focus on specific cell or network needs dynamically, and build network slices on the fly to serve a particular area. Network energy use affects the cost of running the network and its global energy footprint and consumption.

6G connectivity aims to enable sustainable activities in other sectors, such as automotive vehicle-to-everything (V2X) communications and assisted and autonomous driving, smart agriculture, and continuous system monitoring. 6G also must meet the cybersecurity needs of a total coverage network. It must enable the optimization of cross-layer security and zero-trust architectures for full flexibility on disaggregated or multi-vendor deployments.

Joint communications and sensing

6G is exploring using sub-terahertz and terahertz spectra for communications. Wide, contiguous bandwidths are available at these frequencies, making them appealing for high-data-throughput applications.

These frequencies have other advantages. Today, automotive radar operating at frequencies between 76 and 81 GHz creates a map of the environment around a vehicle. But the map is incomplete and requires visual processing. Other imaging applications, like airport security scanners operating at 24.25 to 30 GHz, use millimeter-wave (mmWave) frequencies. 6G looks to take advantage of the inherent ability of mmWave signals for non-ionizing imaging.

The wide bandwidths at sub-terahertz frequencies can potentially use new waveforms that combine a traditional communications waveform with one that looks more like a radar or channel-sounding waveform. By combining these two types of waveforms, a sub-terahertz signal can capture environmental imaging information and communications information. This technique is known as joint communications and sensing (JCAS). JCAS is also possible with non-sub-terahertz signals by examining the known characteristics of waveforms and how they change through a substrate.

JCAS has many potential applications. At its most basic level, it can return distance information to the network using chirp signals. At frequencies above 100 GHz, the resolution of the distance calculation can be 1 cm or less (in practice, this level of resolution is optimistic because of interference from other objects). Engineers can use the delay and Doppler shift of a returned sounding signal or chip to calculate the velocity of an object. A more precise knowledge of the location creates more accurate positioning and enables a 6G network to deliver spatial monitoring.

JCAS can thus improve the vision of an autonomous vehicle enabling it to navigate by navigating through dense fog, for example. In public safety, it can help in search and rescue scenarios by identifying humans in a burning building. Being able to communicate using the same spectrum as advanced imaging and radar devices has two more benefits:

- Enabling these different applications to share antennas and transceiver hardware.
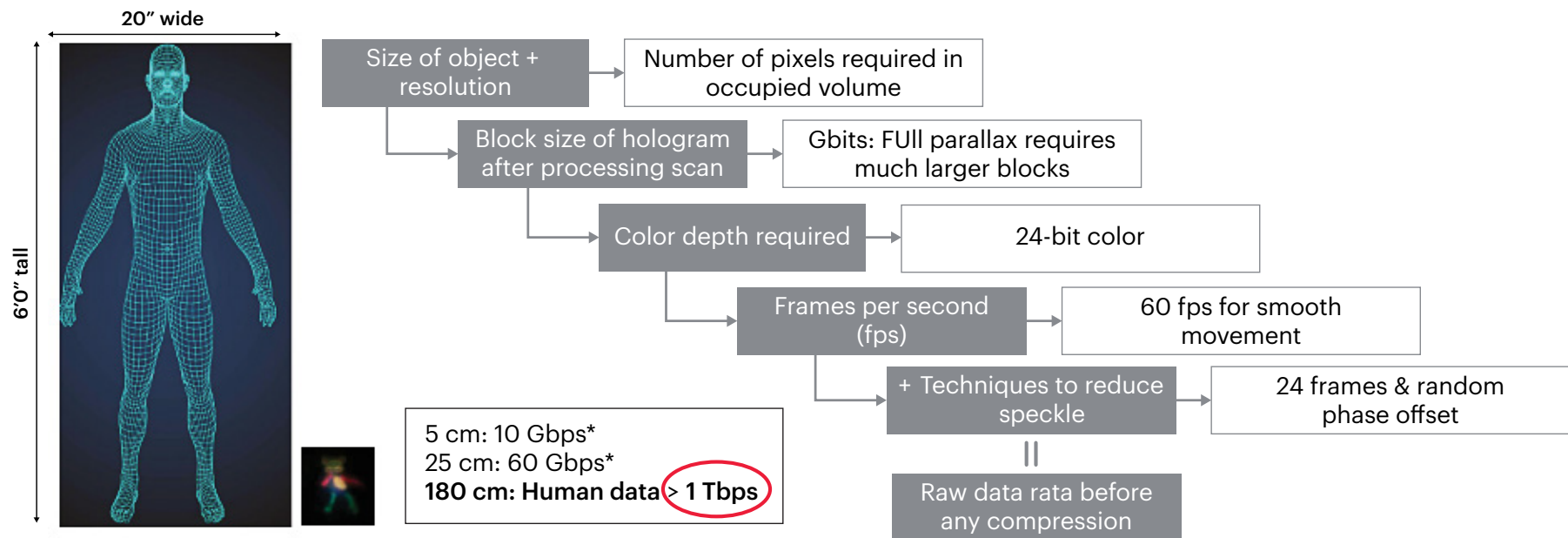
- Enabling them to share spectrum.

Space inside physical devices and spectrum are two of the most limited finite resources in the wireless ecosystem, making JCAS an important area of study for 6G.

Immersive telepresence and virtual and augmented reality

The pandemic forced humans into new methods of living and working together. It reinforced the value of rich, meaningful digital interactions. The 2D video calling available today has made things like remote work and learning possible, but it is no substitute for face-to-face interaction. Adding an extra dimension to telepresence is the first step toward creating more realistic digital interactions and as camera technology and graphics processing units advance, the idea of 3D holographic telepresence is no longer science fiction.

6G aims to build a communications network that can meet the high-data-rate requirements this application requires. While signal compression can help transmit holographic images, the amount of data required to create a realistic hologram is substantial. The low-end estimate of the data rate needed to enable holographic telecommunications is 10 Gbps, with a high end of 1 Tbps. Figure 2 shows how a human-sized hologram requires a 1 Tbps data rate.

Holographic telepresence demands

20" wide

6'0" tall

| Size of object + resolution | → | Number of pixels required in occupied volume |

| Block size of hologram after processing scan | → | Gbits: FUll parallax requires much larger blocks |

| Color depth required | → | 24-bit color |

| Frames per second (fps) | → | 60 fps for smooth movement |

| + Techniques to reduce speckle | → | 24 frames & random phase offset |

||

| Raw data rata before any compression |

5 cm: 10 Gbps*
25 cm: 60 Gbps*
180 cm: Human data > 1 Tbps

*X.Xu, Y.Pan, P.P.M.Y.Lwin and X.Liang, "3D holographic display and its data transmission requirement", Proc. Int. Conf. Inf. Photon. Opt. Commun., pp. 1-4, 2011.

Figure 2. Data rate required for a human-sized hologram

Low latency is not imperative for immersive telepresence. However, it is easy to imagine how virtual reality (VR) applications can reuse the underlying holographic telepresence technology. In addition to sound and holographic images, haptics will make VR sound, look, and feel realistic. Haptics and devices like VR glasses or goggles require low latency and high bandwidths for the experience to feel accurate and to reduce motion sickness.

In augmented reality (AR) applications, the closed-loop data required to transmit the environment a user sees and overlay that with 8k or 10k requires heavy uplink and downlink speeds. Those speeds must reach 10 or 100 Gbps to provide seamless AR coverage.

Entertainment use cases, such as video games and concerts, will use this technology. So will tools such as pedestrian and automotive navigation, which have various density or Doppler challenges. In dense situations such as concerts or urban environments with many pedestrians, these data-hungry devices will push the need for spectral efficiency. They will require new technologies from 6G, such as ultra-massive multiple-input / multiple-output (MIMO) beamforming or distributed MIMO beamforming capabilities. The devices must be reimagined and will likely not use today's dominant handset form factor.

Massive twinning

The idea of creating highly accurate digital copies, or digital twins, of real-world environments, and doing so at a large scale, is known as massive twinning. This application is compelling for industrial use cases and gaming.

In industry, massive twinning will serve as a tool in early design and technology development and for test and validation. Digital twins are similar in concept to emulators, but users can update them with real-world data from sensors and measurements. The proliferation of connected sensors will enable higher fidelity and dynamic digital twins that can change and adapt to mirror real-world environments.

Digital twins can evaluate new technologies to better understand performance and make design decisions informed by real-world performance before engineers build physical systems. After companies create and deploy devices, they can use massive twinning to reduce risks associated with making software updates. In cellular systems and more generally, software-defined products are becoming the norm. The increased use of software in devices has come with a proliferation of software updates. Massive twinning enables developers to test and validate software updates in a highly accurate emulation environment before pushing them to customers and end users.

In gaming, being able to build an alternate reality that can change, adapt, and mirror the real world has attracted significant hype. The idea of a massive twin of our reality combined with immersive virtual reality brings to mind science fiction examples like the holodeck on Star Trek. While 6G won't get us the holodeck, it will advance the fundamental technology required to build it. For example, using connected devices and sensors to create digital mirror worlds will begin in 6G. As mentioned in the "Immersive telepresence and virtual reality" section, the high bandwidths and low latency of 6G will enable the transmitting and receiving of holographic images integrated with audio and haptics.
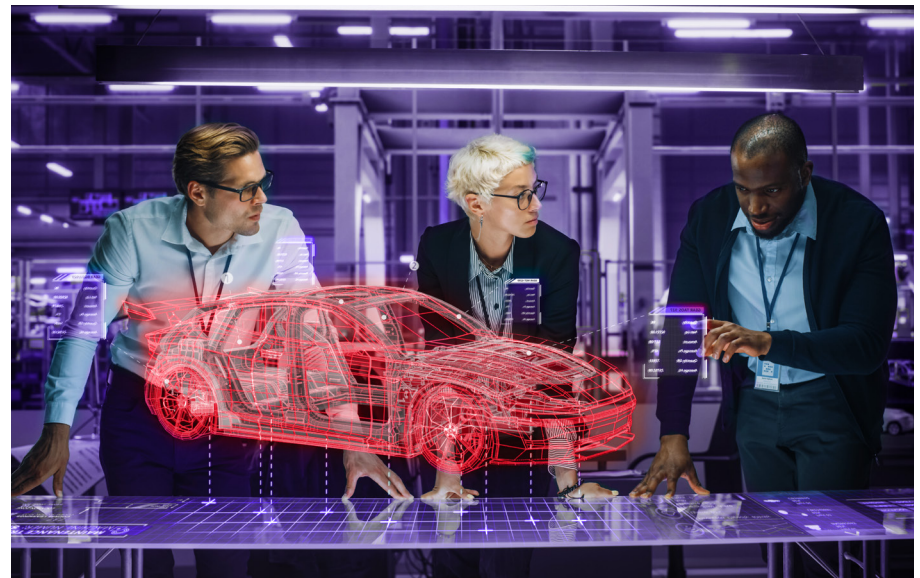
Sustainability

For the first time in any wireless generation, sustainability is an essential KPI. We can look at sustainability in two key ways:

- How can we make our wireless ecosystem more sustainable?

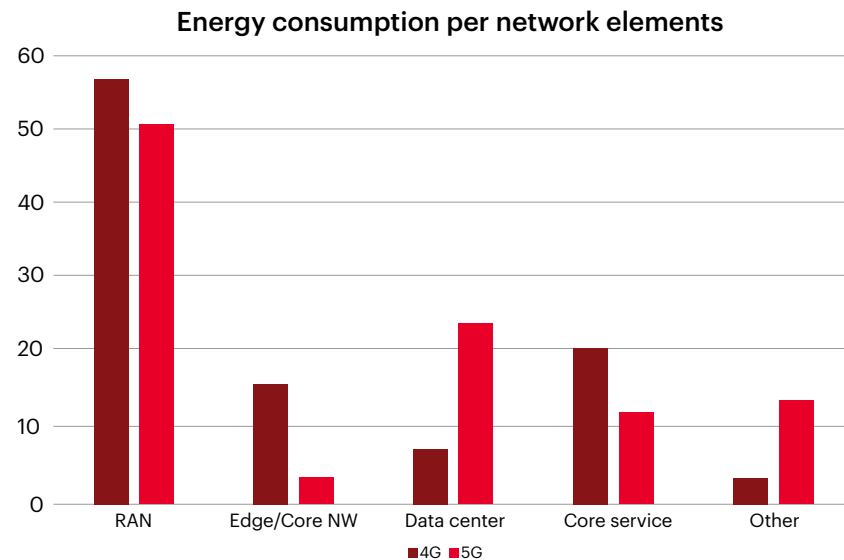- How can we use 6G to enable sustainability in other applications?

Energy consumption per network elements

Figure 3. Next G Alliance's percentage of energy use in wireless networks (Source: The Next G Alliance)

Sustainability of wireless systems

Wireless systems and networks consume large amounts of resources, from electricity to raw materials. The power required to run networks is massive. In 2020, for example, China's mobile networks and data centers consumed approximately 201 terawatt-hours of energy. This equates to roughly 2.3% of the total energy consumption of the entire country. Given the pace of 5G network deployment, consumer demand, and the shift toward using data centers to run virtualized mobile networks, energy use by wireless networks in China is expected to grow 289% between 2020 and 2035, according to a Greenpeace study. To meet the electricity needs of this growth rate, future networks must be more energy efficient. The radio access network (RAN) is an obvious place to start.

GSMA Intelligence published a report looking at network energy efficiency. It found that the RAN consumes 73% of the energy network operators use. But other areas deserve consideration. Figure 3 shows the dramatic increase in energy used by data centers in 5G versus 4G. This trend will likely continue. The decentralization and virtualization of the RAN popularized by Open RAN initiatives will push processing traditionally done in the RAN into software-based (O-DUs) decentralized units and (O-CUs) centralized units.

Statistics like these make power reduction an easy area to focus on for future networks. Mobile network operators are already shifting to renewable energy sources to power their networks, with approximately 46% of electricity coming from renewable sources globally. Meeting net-zero goals requires further reductions.

Work has begun in 5G to make base stations more efficient, and 6G looks to take those efforts to the extreme. Techniques like turning off power amplifiers and other components when they are not in use, sometimes referred to as "sleep mode" or "deep sleep mode," have proven useful in early deployments. But these methods require refinement and optimization. The systems must remain off long enough to offset the energy required to turn them off and back on, as demonstrated in Figure 4. Machine learning can help solve this optimization problem and provide better results than a rules-based approach.

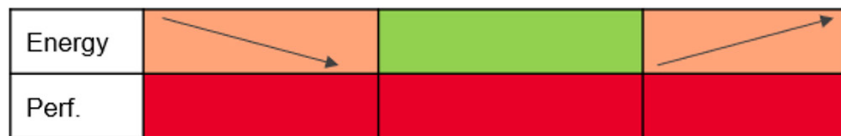| Sleep level	Deactivation duration	Minimum sleep duration	Activation duration
SM$_1$	35.5 µs	71 µs	35.5 µs
SM$_2$	0.5 ms	1 ms	0.5 ms
SM$_3$	5 ms	10 ms	5 ms
SM$_4$	0.5 s	1 s	0.5 s

Figure 4. Advanced sleep mode characteristics and visualization (Source: IEEE)

As an industry, and as mobile device consumers, we must look at the entire device supply chain and life cycle. Improving resource efficiency, increasing electronics and battery recycling, using more sustainable materials, and developing new materials for batteries are all important research areas for 6G sustainability. Developing and standardizing new metrics and KPIs will help define goals around sustainability and efficiency.

Measuring the total carbon footprint of a wireless network is a key challenge to overcome. There are three types of emissions: scope 1, 2, and 3.

Scope 1 emissions are direct emissions. They include emissions from burning coal to create electricity at a power plant and emissions from vehicles in a company fleet. Scope 1 emissions are typically the easiest to measure.

Scope 2 emissions come from indirect use. Emissions from purchased electricity, heating, and cooling fall under scope 2. For example, purchasing electricity generated by renewable sources can reduce scope 2 emissions. They are relatively easy to measure, but doing so requires transparency from vendors and suppliers.

Scope 3 emissions, classified as indirect emissions related to the upstream and downstream supply chain, account for the largest portion of emissions for most companies. They are the most difficult to measure and reduce, requiring close partnership and collaboration among all vendors and suppliers across the supply chain. Work is underway to better measure emissions and create standards around sustainability. These combined efforts will give industry and consumers the transparency and clarity needed to make 6G green.
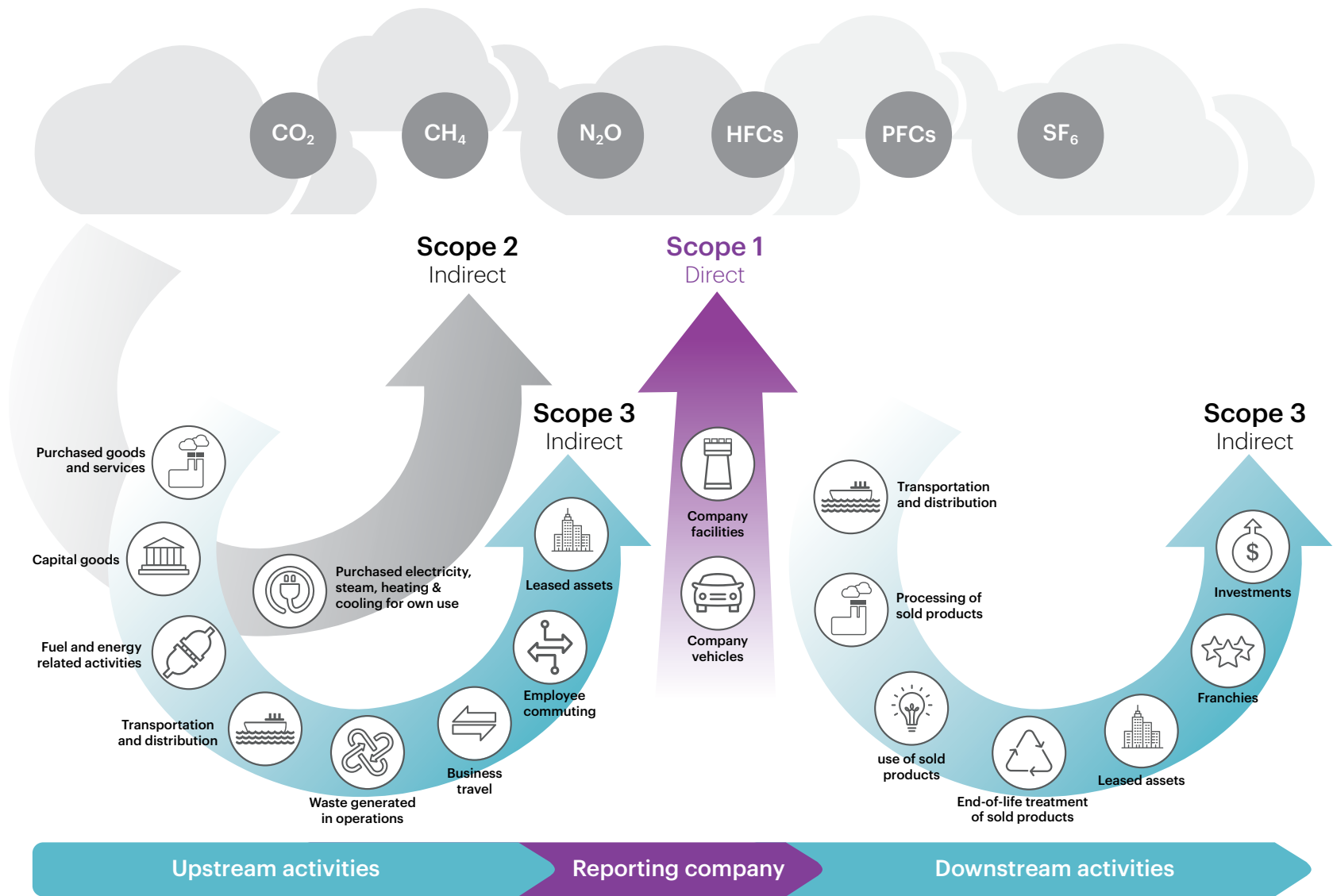
Figure 5. Overview of emissions scopes (Source: Greenhouse Gas Protocol, World Resources Institute)

Enabling sustainability in other industries

5G greatly increased the number of devices connected to cellular networks. The number will continue to grow as use cases like private networks and the Industrial Internet of Things reach critical mass. Massive amounts of data created by smart devices, combined with Artificial Intelligence (AI) and Machine Learning (ML) built into 6G, will give the industry deep insights that various sustainability-related applications can use.

In manufacturing, wireless connected machines will help with predictive maintenance by analyzing trend data and monitoring machine performance. This information can improve yield through trend and failure analysis. Augmented and virtual reality will make it easier for humans to interact with machines, helping them troubleshoot problems quickly and reduce downtime. In farming, 5G and 6G can monitor soil conditions and help optimize water use and fertilizer.

In automotive, V2X has started to define a way for cars to communicate with each other and cellular infrastructure. 6G looks to leverage joint communications and sensing to help our cars "see." These improvements will help autonomous vehicles become more advanced, which has the potential to greatly reduce traffic and the waste and inefficiencies associated with driving. As more devices and machines become wirelessly connected, there is more opportunity to optimize their operations and reduce their carbon footprints.

Many challenges lie ahead for building a sustainable, green wireless communications ecosystem. Developing and standardizing on ways to measure and communicate sustainability are crucial. Consumers will benefit from and are asking for markings like the Energy Star rating that the United States uses. Consumer demand for sustainable wireless technology is driving change in Europe. A transparent, consistent, and easy-to-read rating system will allow consumers to make informed purchasing decisions. Standardizing on sustainability measurements will allow companies to quantify the performance of their devices systems and improve them. The focus on sustainability in wireless communications shows that industry is serious about tackling these challenges and that 6G can make the world a better place.

The Evolution of 5G

While 6G promises to be revolutionary and vastly different from 5G, it will also be an evolution. It will build on many of the concepts and technologies introduced in 5G. The completion of 3GPP Release 15 and Release 16 and the subsequent commercialization of these specifications do not signal that 5G New Radio (NR) is complete as a standard.

3GPP Release 8 defined the LTE standard and continued to Release 14, with LTE updates still coming in Release 15 and beyond. Some aspects of 6G will be built from the ground up, using the new generation as an opportunity to start from scratch. Artificial intelligence (AI) and machine learning (ML) networks, for example, will benefit greatly. However, other aspects of 5G will continue to evolve and form the foundation for 6G. This chapter explores the evolutionary aspects of 6G.
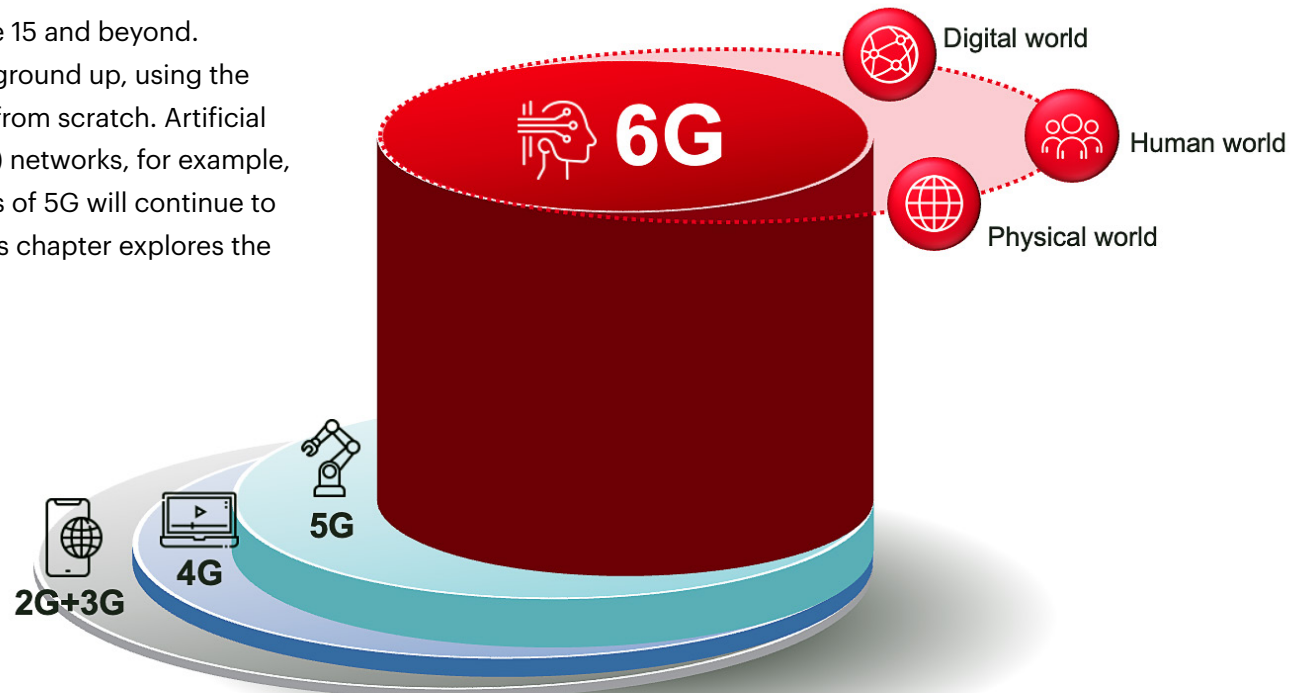

Figure 6. 6G's Evolution to incorporate the digital, physical and human worlds

3GPP standardization timeline

Over the next decade, cross-industry collaborations and a complex web of technologies will reshape businesses, industries, and our lives.
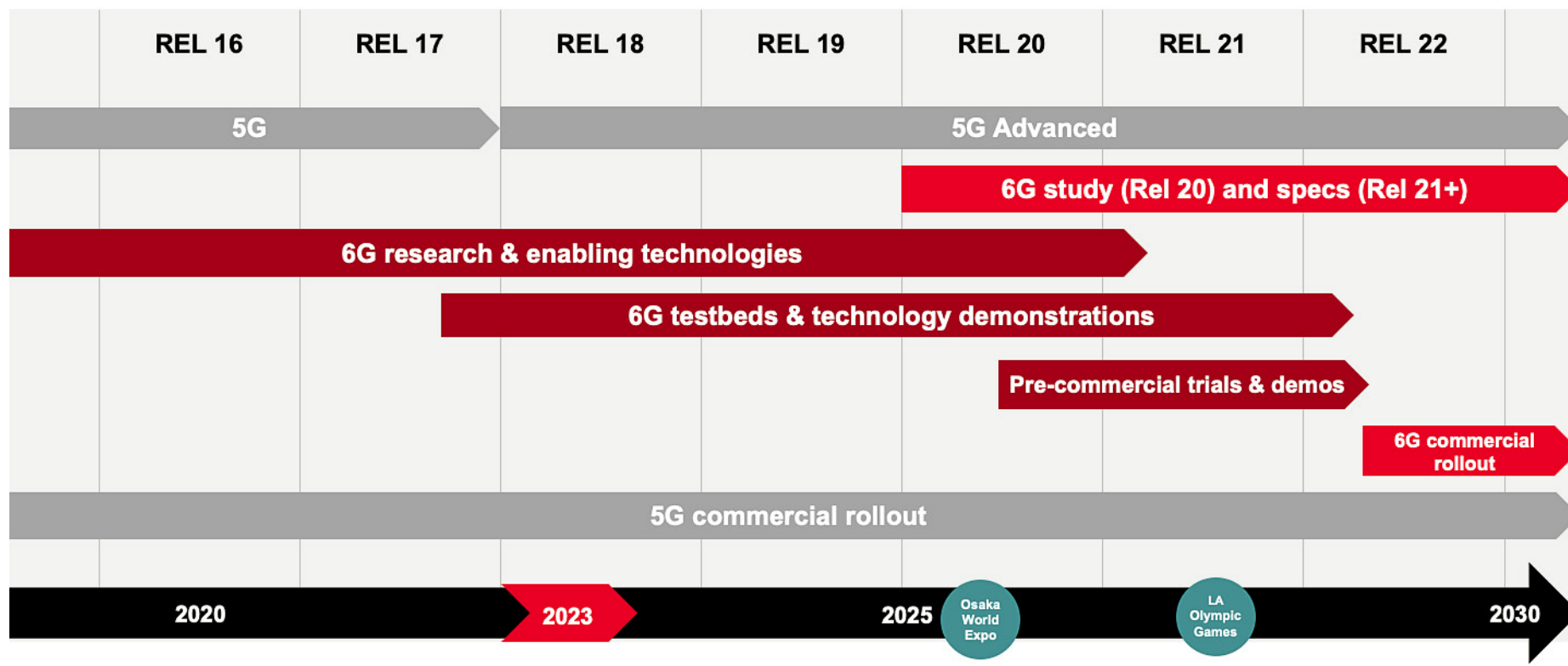

Figure 7. Expected 5G progression and 3GPP timeline for 6G

Figure 7 shows the expected evolution of the 5G standard. Driven by the Third Generation Partnership Project (3GPP), it will roll out alongside the development of 6G technologies and standards. The top left of the diagram shows the timing of Release 16's performance requirements, followed by Release 17 in mid-2022. Agreement on the scope of Release 18 also occurred in mid-2022. Releases 16, 17, and beyond — known as the 5G Evolution — bring enhancements and extensions of the original Release 15 5G NR standard. Figure 7 shows 3GPP's release timeline as of March 2022.

When advanced wireless research shifts from 5G to 6G, it is primarily a change in standardization terms or marketing rather than a shift to something entirely new. The first 3GPP 6G release will open the door to new technologies and changes to fundamental technologies (will we see a new waveform in 6G, for example). However, these concepts and ideas are already forming as a natural progression of the research completed for later 5G releases.

6G research is developing new and unique capabilities built on 5G. The number and variety of technology demonstrations and trials will increase through 2030, augmented by 6G test beds (such as test networks of all types). 6G standardization work should begin in earnest around 2025 when 3GPP plans to initiate Release 21, with deployment expected before the end of the decade.

As with 5G, countries and mobile operators will race to declare the first commercial 6G service near the end of the decade. Proposals for public pre-standardization demonstrations will come as early as 2026 but more likely will occur in 2027 and 2028. In the years that follow, successive waves of 6G technologies will come to market, fulfilling the 6G vision through the 2030s.

Some technologies proposed for 5G will continue to evolve throughout the 5G Advanced and early 6G releases. Non-terrestrial networks, radio access network decentralization, and AI and ML fall into this category.

6G Technologies

6G has set out to accomplish a broad range of goals, requiring a broad range of technology. As with 5G, no single technology will define 6G. The groundwork laid out in 5G will serve as a starting point for 6G. But because 6G will be a distinct new generation, there is also an opportunity to break with previous revisions and introduce new concepts. At Keysight, we have grouped similar technologies into four pillars to organize the numerous research threads happening for 6G. Time will tell which technologies become part of the standards and proceed to commercialization.

Because of the natural evolution and advancement of wireless standards, the technologies in each pillar will change and adapt over time. Still, we believe these four pillars encapsulate the core technologies of 6G. These pillars are new spectrum technologies, AI and ML networks, digital twins, and new network topologies. The remainder of this eBook will provide an overview of the technologies that make up each pillar.

Four Key Technologies Shaping 6G

Keysight is accelerating 6G by pushing the boundaries of technology in four crucial ways:

New Spectrum Technologies
- 6G requires higher frequencies to reach its full potential and will use the sub-terahertz (100–300 GHz) and terahertz (up to 1 THz) bands.
- Higher frequencies might demand a shift to new waveforms, like orthogonal time frequency space (OTFS) or scrambled code multiple access (SCMA).
- Solutions like massive multiple input and multiple output (MIMO) and reconfigurable intelligent surfaces (RIS) will evolve and make the most out of the terahertz band, maximizing 6G capabilities.
- Full duplex transmission, which can double network capacity, was not ready for 5G but will help 6G process heavy data traffic.

AI & ML Networks
- With the growing virtualization of networks, artificial intelligence (AI) and machine learning (ML) will under lie every step of telecommunication.
- Unlike 5G, 6G networks will have AI and ML integrated from the start.
- AI and ML will play a central role in spectrum management, security, radio access network (RAN) planning, network automation, and much more.
- AI and ML will help increase the network performance by making it more intelligent and efficient.

Digital Twins
- Creating a virtual replica of anything — from networks to cities — will revolutionize how the world tests and measures.
- Assisted by AI and ML, digital twins allow for zero-risk environments for testing.
- Digital twins reduce expenses by identifying optimal performance and providing a low-cost test environment — no need for prototyping.
- Digital twins can also be applied to gaming, entertainment, and education, creating "phygital" experiences.

New Network Architectures
- Forthcoming 6G networks will rely on open, scalable, and virtual networks working together.
- Non-terrestrial networks promise to maximize the 6G range and deliver signals to underserved communities.
- Private networks will provide industry and internet of things (IoT) connectivity.
- Time sensitive networks will ensure reliability as 6G operators accurately determine the network's latency.

1   2   3   4

6G Innovation Starts Here

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New spectrum technologies

The extreme data rates of sub-terahertz bandwidths and potential sensing applications will work in concert with spectral efficiency techniques like MIMO, reconfigurable intelligent surfaces, and full duplex to deliver ubiquitous coverage for 6G communications.

Ultra-massive MIMO

Spectral efficiency is an ever-iterating system optimization problem. Wireless standards are always evolving to best use the bandwidth available for a given frequency band. In 5G, MIMO and massive MIMO technologies found their footing as a major enhancement to radio systems by combining multiple transmitters and receivers into one system and using constructive and destructive interference to beamform information toward users with greater signal resiliency.

5G MIMO appears primarily in the sub-6 GHz bands to provide coverage in macrocell environments. It enhances capacity and throughput via spatial multiplexing to provide coverage precisely where needed. Massive MIMO, typically thought of as greater than 16 antennas transmitting and 16 antennas receiving, allows orders-of-magnitude improvements as the number of antennas increases. 5G massive MIMO complexity capped out around 64 x 64 antennas, but prototype systems of up to 256 were part of the early-stage MIMO developments in 5G.

In 6G, MIMO is looking to scale the commodity improvements in radio hardware and processing capabilities from hundreds of antennas to thousands to provide even greater data rates to users and hyperlocalized coverage in dynamic environments. Implementing these ultra-massive MIMO systems presents several challenges.

First, synchronizing and handling the phase noise offsets between multiple channels at scale is difficult and requires frequent calibration or continuous algorithmic compensation. Drift across local oscillators can hinder the reconstruction of uplink signals or provide proper coherent beamforming and can restrict the usability of ultra-massive MIMO radio systems. Antenna systems for 1,000 independent radio channels would be costly and require immense power and cooling, even with MIMO gain offsetting the need for preamplifier gains.

Potential solutions to the antenna systems would be reconfigurable intelligent surfaces, which could merge physical and digital beamforming technologies and simplify ultra-massive MIMO deployments. Networked MIMO systems are an alternative to the 1,000 antenna goals for MIMO. These systems would reconstitute radio channels across multiple distributed radio units to create beams from existing deployments and turn multiple colocated base stations into a single MIMO transceiver capable of beamforming for coverage. This method requires distributed synchronization and a well-understood channel model but has major upsides for distributed deployments of radio access network (RAN) equipment in disaggregated networks.

Reconfigurable intelligent surfaces

The high free space path loss and ease of blockage are challenges for millimeter-wave (mmWave) and sub-terahertz signals. Reconfigurable intelligent surface (RIS) technology offers a promising solution to overcome those difficulties.

A RIS is a flat, two-dimensional structure consisting of three or more layers, with a top layer containing multiple passive elements that reflect and refract incoming signals. Engineers can program the elements in real time to control the phase shift.

Because engineers can control the phase shift of each element, a RIS can reflect signals in a narrow beam to a specific location. A RIS can positively interact with reflections coming from the source signal to enhance the signal strength. A RIS can negatively interact with the source signal to reduce interference in dense multi-user environments or multicell networks. This flexibility allows RIS technology to help extend the signal range and enhance security. The antenna array created by the elements of the RIS is inherently passive, making RIS a possible solution for high-density, low-energy-consumption deployments.

Research on multiple RIS types is underway. The most common is a PIN diode RIS. A PIN diode RIS typically contains three layers: printed reflecting elements, a copper backplane, and a control circuitry layer. A field-programmable gate array often serves as part of the controller with this architecture.

To create the phase shift in each element, the voltage of a biasing line switches between on and off. Multiple PINs can integrate into each element to increase the granularity of phase shift. When multiple elements combine, beamforming is possible.

Liquid crystal and transparent are two other RIS types of interest. A liquid crystal RIS is similar to a PIN diode RIS, but it varies the voltage applied to liquid crystal molecules to vary the phase instead of a bias line and PIN diode. The reflective layer of this type of RIS is also different and uses multiple layers, including a patch, a slit, and a time-delay line. It is less costly to make and uses less power but has a higher insertion loss than a PIN diode RIS.

Transparent RIS with transmissive properties would allow users on the other side of the RIS to receive a signal that may be otherwise blocked — for example, going from the outside of a building to the inside. This type of RIS could be applied to windows, walls, or other indoor and outdoor glass surfaces for better indoor coverage.

New frequency bands

Looking back, every generation of cellular technology has added new spectrum, and 6G will be no exception. New use cases and a continually growing user demand for high-speed data mean that 6G must be capable of delivering high data throughputs. 5G has brought about a massive increase in speed over 4G by using new frequency bands. Underutilized mmWave bands have great potential to deliver more data throughput. Expansions to new bands below 8 GHz leverage massive MIMO technology to increase spectral efficiency.
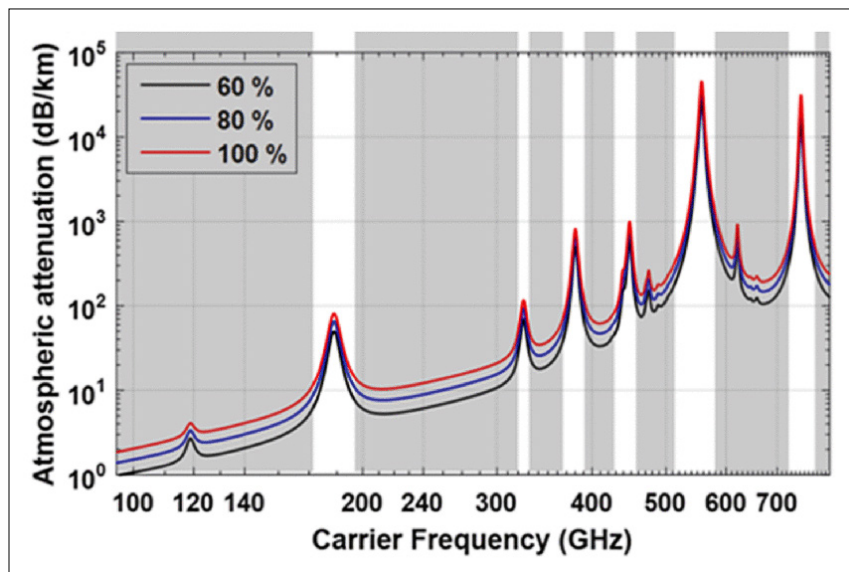

Figure 8. Attenuation of signals as frequency increases / wavelength decreases (Source: Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond)

6G will continue both of these trajectories. Two bands under consideration for 6G are between 100 and 300 GHz, often called sub-terahertz bands. Early test beds already exist to prototype communications at sub-terahertz frequencies. Channel models for D band are a first step to gaining deeper knowledge about the channel conditions and propagation characteristics of sub-terahertz signals. Other research is looking at novel techniques and substrates needed to build integrated circuits operating at these frequencies and bandwidths. Bringing commercial communications applications to these frequency bands is a new area requiring extensive research. This area covers many engineering disciplines, including novel antenna design, digital signal processing, and new air interfaces.

One of the challenges of using sub-terahertz signals for wireless communications is the free space path loss at these frequencies. Early researchers and groups like the International Telecommunication Union selected the frequency bands they are considering for 6G to minimize path loss. One way to mitigate path loss is by using antenna arrays.

Since wavelength is inversely proportional to frequency, the size of antenna arrays can be quite small. For example, at 28 GHz, a 1 x 4 array is typically 20 mm x 5 mm. At 140 GHz, a 4 x 4 array would only be 5 mm x 5 mm. This small antenna size is appealing and could benefit new 6G devices like wearables.

Expansion into sub-terahertz frequencies is not the only new spectrum targeted for 6G. The spectrum between 7 and 24 GHz is also under consideration. This spectrum has a number of government and satellite incumbents today, but some bands could potentially work for mobile communications. If communications engineers can develop techniques for better spectral sharing, the potential use cases for those frequencies will also increase. While there are regulator challenges to overcome, the 7 to 24 GHz band holds tremendous value for wireless communications because of its favorable propagation characteristics.

Full duplex

For more than a decade, communications researchers in industry and academia have been investigating how to double the capacity of a radio channel by enabling simultaneous transmission (Tx) and reception (Rx) of signals on a single channel. Transceivers transmit and receive at different frequencies (frequency-division duplex, or FDD) or different times (time-division duplex, or TDD). From walkie-talkies to police radios to mobile telephones to avionics and satellite communications, the technology on the front end of radio transceivers has focused on duplexing filters (for FDD) or TDD switches (to switch off the transmitter during the allotted times for reception).

With most systems using the same antenna for Tx and Rx, the significant difference between transmit and receive power means that, to receive a weak signal from a distant transmitter, either the local transmitter is switched off during reception or it is transmitting

on a different frequency. This requires two radio channels for duplexed communication or one channel with the capacity divided between transmit and receive.

Continued advancements in radio and digital technology are opening the way for something called in-band full duplex (IBFD). IBFD uses an array of techniques to eliminate self-interference so that the receiver can maintain high sensitivity even while the transmitter is operating on the same channel simultaneously. Architectures vary, but the general approach follows three stages of self-interference cancellation (SIC).

5G mmWave

RF frequency: 28 GHz
Channel BW: 400 MHz
UE 4 TX – AP: 64 RX antennas
Modulation: 64 QAM
Data rate: 1.6 Gbps (UL)
UE TX AFE:
• Pdc: 360 mW
• Energy / bit: 0.22 nJ / bit
• PDC 1 Gbps (DC): 230 mW

Beyond 100 GHz connectivity promises extreme data rates at smaller form factor and higher energy efficiency

6G sub-THz

RF frequency: 140 GHz
Channel BW: 5000 MHz
UE 16 TX – AP: 256 RX antennas
Modulation: 16 QAM
Data rate: 13 Gbps
UE TX AFE:
• Pdc: 1400 mW
• Energy / bit: 0.1 nJ / bit
• PDC 1 Gbps (DC): 108 mW

20 mm

5 mm

5 mm

5 mm

Figure 9. Antenna array size versus frequency

The first stage is close to, and sometimes part of, the antenna itself. It typically uses electromagnetic means to reduce the energy from the transmitter that gets into the receive path. The simplest forms are variations of RF circulators. These three- or four-port devices allow most of the RF power entering one port to exit only one other port.

The second and third stages of interference cancellation benefit from the transceiver "knowing" the transmitted signal. These stages use phase-reversal cancellation methods. The second stage is typically analog. The third stage of interference cancellation is often active analog cancellation in the RF domain. The Tx signal scales and feeds back into the Rx signal path (after the antenna and circulator). Given this feedback, destructive interference further reduces the energy from the Tx that makes it past the circulator. The final stage occurs in the baseband domain and, in principle, further cancels the Tx interference in the Rx path, given complex feedback techniques.

The three stages of SIC are necessary because the Tx signal at the antenna can be 110 dB higher than the Rx signal. None of the individual techniques described above provides anything near the 120 dB of cancellation required for an effective 10 dB SINR.

Some commercial radio systems for use in point-to-point communications successfully implement IBFD. While it remains impossible to reach the theoretical limit of doubling the capacity of the RF channel, some significant progress has occurred. The challenge, however, is in the added complexity and cost of the transceiver and the problems caused by the rest of the channel.

If the only Tx energy the SIC had to account for was at the immediate antenna aperture, interference might be easier to manage. However, the Tx signal enters the radio channel and is subject to multiple reflections, each with a different time delay with respect to the Rx path. This process is even more complex, given that some of these reflections will also have varying Doppler shifts.

Thus, SIC must account for reflections in the channel that become much more pronounced in mobile wireless access systems (point to multipoint). The work to address these issues continues, and we could see significant progress in 6G given applications of everything from new materials science to AI.

IBFD, or as some call it, single-frequency full duplex (SFFD), has moved far enough to be under investigation by the Third Generation Partnership Project (3GPP) in Release 18. This step toward SFFD is known as sub-band full duplex. For this to be feasible in a standard used in production networks within a few years, 3GPP is taking small steps rather than a full leap to SFFD on mobile and base stations. The base stations will not manage full duplex across the entire radio channel but rather across a portion of it.

In addition, mobile devices (user equipment) will not implement any SFFD. This functionality takes advantage of point-to-multipoint communication. The simultaneous Tx and Rx at the base station means the base station is transmitting to one mobile device and receiving from another at the same time, with the UL sub-band sandwiched between the downlink sub-bands. For this to work, SIC as described above is not the only technology. At the base station, the system will also leverage newer antenna systems that will use separate antenna beams for uplink and downlink. In a way, this is building a fourth stage of SIC into the antenna itself.

This work is a step toward SFFD. Like other techniques to realize 6G, it will benefit from further technological development and the results of significant research.

New waveforms

New physical-layer waveforms are a topic of debate in each generation. Orthogonal frequency-division multiplexing (OFDM) is the waveform used in 4G and 5G, but 6G may look to change that. While OFDM has advantages, the required signal flatness is hard to achieve in RF amplifiers for wider bandwidth signals, even with advanced digital predistortion (DPD) techniques. Developers have proposed wider bandwidth signals for frequencies above 50 GHz, and amplifier design at those frequencies is already a challenge without the flatness requirements of OFDM.

Aside from challenges with RF components, there are other reasons to believe that 6G will use different waveforms. Joint communications and sensing, for example, requires waveform modifications to accommodate communications signals and the signals required for sensing. Advances in AI and ML present an interesting opportunity to reconsider what a physical-layer waveform is at a fundamental level. Previous generations have been bound to use fixed waveforms and have focused on quadrature modulation schemes. AI- and ML-based physical layers could use an adaptive PHY with adaptive modulation that looks nothing like the quadrature modulation schemes communications engineers are familiar with.

AI-designed waveforms promise to improve power efficiency and make wireless systems more secure. But breaking away from OFDM waveforms will be a significant challenge in an industry that has perfected an OFDM-based supply chain capable of squeezing out high-performing components with high yields and minimal research and development investment required to implement new features. Arguably, chipset vendors' and manufacturers' exceptional ability to fabricate OFDM-based transceivers is a key reason 5G did not adopt a new waveform.
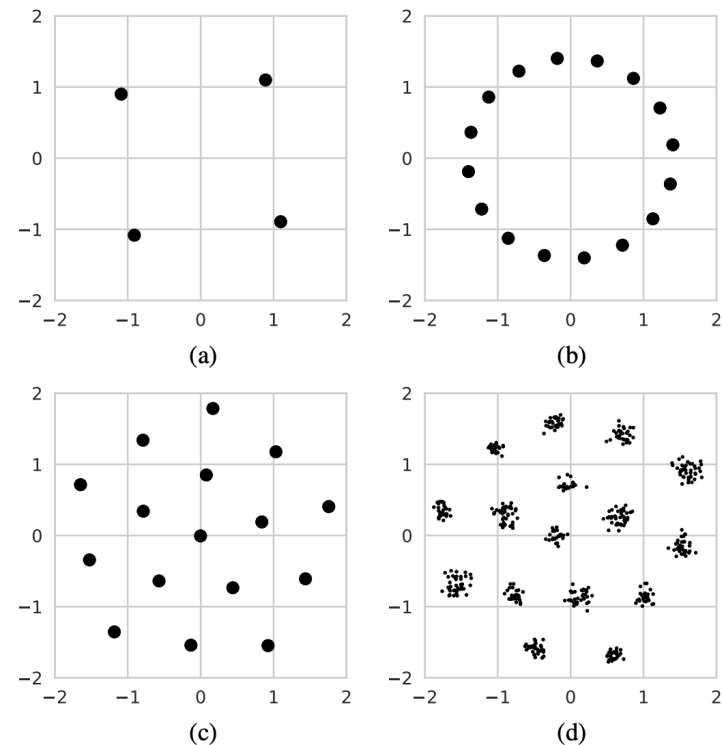

Figure 10. Constellations produced by autoencoders using parameters (n, k): (a) (2, 2) (b) (2, 4), (c) (2, 4) with average power constraint, (d) (7, 4) 2-dimensional t-SNE embedding of received symbols (Source: An Introduction to Deep Learning for the Physical Layer)

Artificial intelligence and machine learning networks

Two foundational technologies for 6G are machine learning and artificial intelligence, but they are not new to wireless networks. It is not an exaggeration to say that in 6G networks, AI will be everywhere. Wireless networks already use AI. The O-RAN Alliance incorporates AI and ML into the RAN intelligent controller (RIC) via xApps and rApps.

The 3GPP completed a study for 5G RAN architectures using AI and ML in March 2022. The study investigated three main use cases: network energy savings, load balancing, and mobility optimization. Network energy savings focused on the whole RAN through traffic offloading, coverage modification, and turning off inactive cells. Load balancing looks at ways to apply AI to distribute network loads to multiple cells, multiple frequencies, or multi-RAT deployment to achieve better network performance. The mobility optimization use case looks at how predictions about the mobility of user equipment can help maintain network performance under various mobility scenarios.

After completing the study, 3GPP decided on use cases for further consideration and agreed that a functional framework is necessary to act as a guideline. Standards bodies like the 3GPP play an important role in ensuring that wireless networks add AI and ML effectively, fairly, and securely.

Outside of the 3GPP, AI and ML are aiding in hardware design. ML enables engineers to optimize transceivers, RF front ends, and antenna systems. This work will continue and will likely aid in examining the entire RF chain. ML is also under consideration for innovative ways of conducting baseband processing. In 5G Advanced, ML replaces and enhances individual blocks like channel estimation and decoding. Early efforts have focused on receivers but will expand to the transmit chain. As ML progresses, it will replace multiple processing blocks within the receive chain, which is likely to happen during 5G Advanced. For 6G, it is possible that ML could design the entire physical layer itself.

A fully AI-designed air interface has implications for all wireless engineers. For example, if engineers use AI to develop the air interface, will they share the design with different operators? Will chipset manufacturers need to make transceivers that are compatible with multiple waveforms? Will the waveform used in 6G be OFDM based? And if not, how is the performance of a transceiver validated? Will error vector magnitude continue to be the gold standard of measurement? Will DPD still be applicable and necessary for power amplifiers, or will AI find a way to make it obsolete? These are all important questions to consider.

In addition to aiding in design, AI will help solve optimization challenges in wireless networks. For example, AI can help optimize the latency of a wireless network. In terms of optimizing for latency, there are different levels of optimization, each with different constraints and KPIs. In a city-wide network, latency will be a matter of seconds. If the optimization is cell-wide, the latency will be in the millisecond range. AI can help with both use cases, but each will require different algorithms, techniques, and training data.
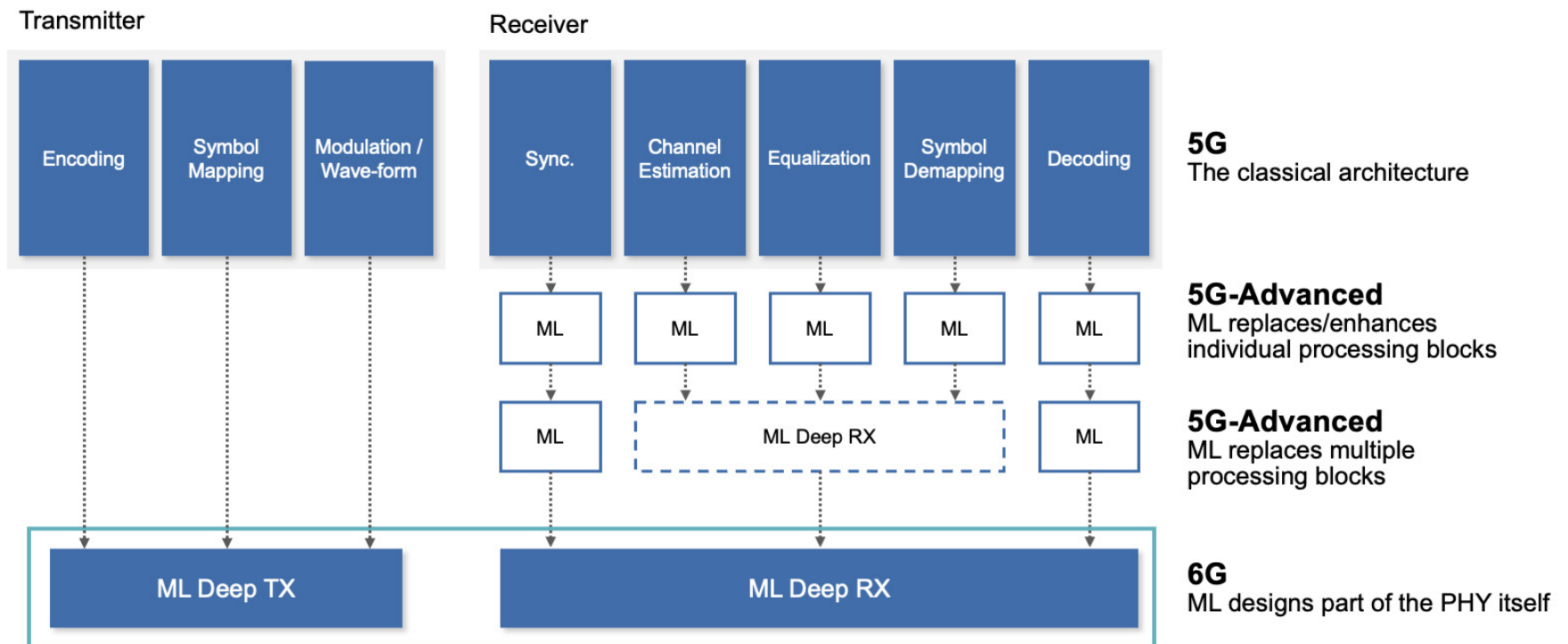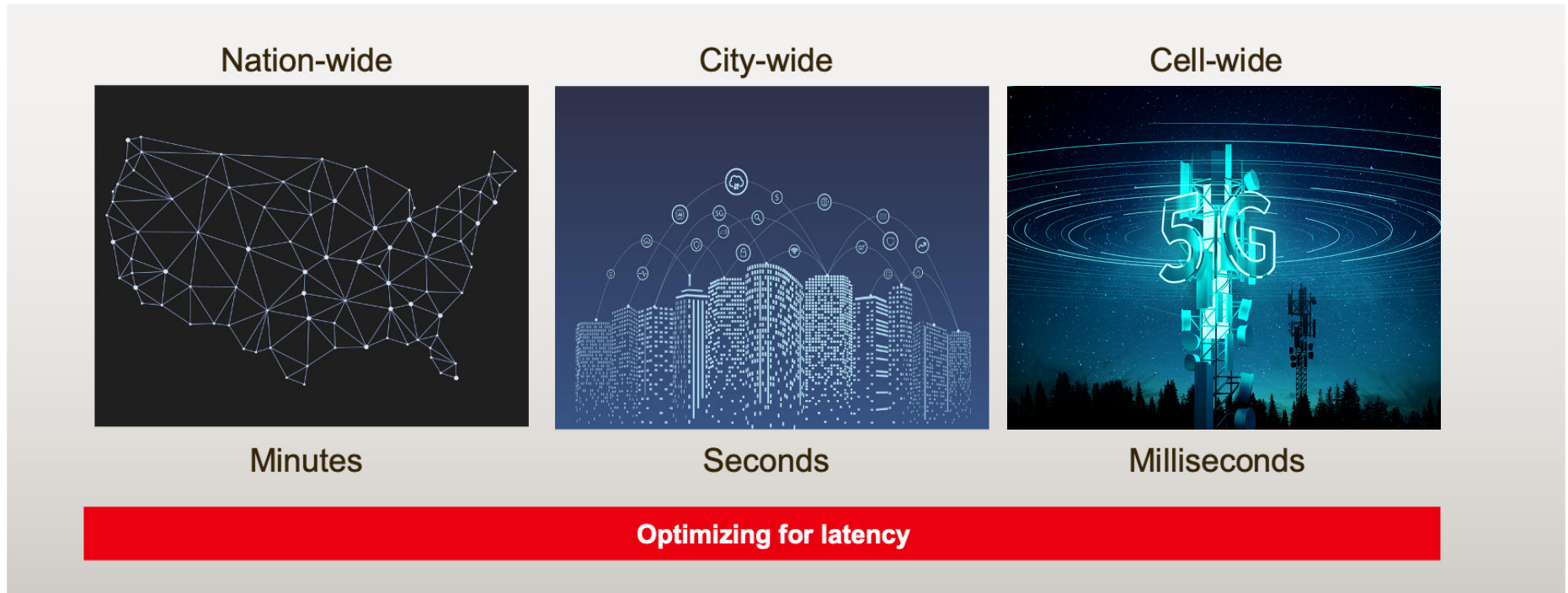

Figure 11. Proposed migration to ML-based PHY for 6G (Source: "Toward a 6G AI Native Air Interface," IEEE Communications Magazine, May 2021)

AI driving network optimization at multiple levels

Latency is just one area for improvement. Capacity and power are other areas. Optimizing the power consumption of wireless systems is already underway in 5G. Turning components on and off to save power when they are not in use delivers significant energy savings. Machine learning can improve these savings across the ecosystem, from cell-wide to nationwide.

Digital twins

One of the most disruptive technologies for 6G design is digital twins. Digital twins are software-based implementations of physical systems. They are similar to a simulation but connect by a data feedback loop that allows for real-time integration of changes to the physical or digital system.

The value of the digital twin workflow is that it enables iterative system validation before pushing changes to the hardware. As 6G moves into the prototyping and development stage, two key digital twin tools will be critical to efficiently and cost-effectively designing 6G: circuit-modeled digital twins and network digital twins.
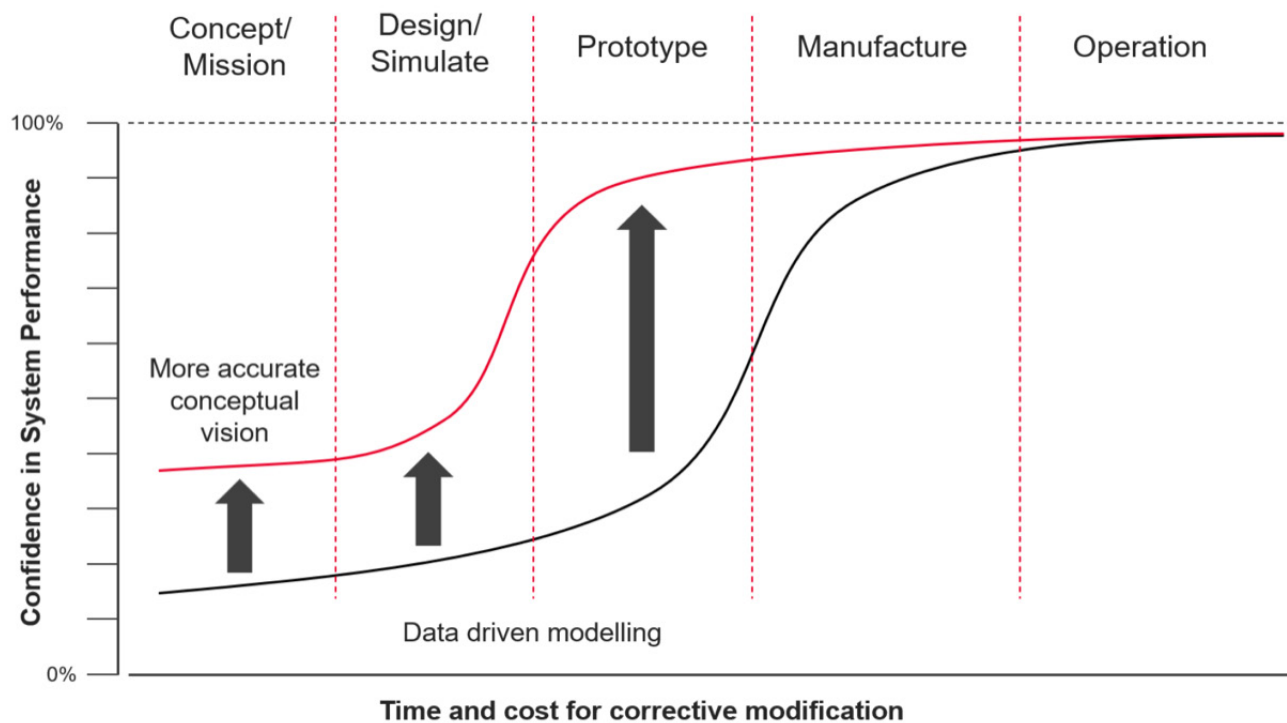

Figure 12. Digital modeling increases system performance confidence (Source: Dr. Ray Kolonay, Air Force Research Laboratory)

Circuit digital twins

The digital twin concept aims to convert most, if not all, physical system engineering activities into virtual ones. Digital twins have high value where staging physical testing is hard and real-world effects are difficult to reproduce, such as in 5G, radar, satellite, and other RF system scenarios. RF circuitry's high level of complexity and costly components, especially in higher frequencies like mmWave and terahertz bands, make the design process difficult to iterate on. Because traditional modeling tools need highly sophisticated processing to accurately represent complex RF circuits, digital twins can provide an advantage by characterizing the responses of the physical circuit and feeding that back into the digital representation.

Digital twins also streamline the supply chain handshakes between component developers and system integrators, as the digital models can be shared and dynamically linked to give integrators earlier delivery of component designs that are updated in real time. By maintaining a digital twin of circuit components, digital twin development workflow, seen in Figure 13, rapid iteration in software models can provide optimization insights or alerts to developers while the device is being changed in the physical process. In 6G, these techniques will be necessary to build complex, high-frequency components that will be costly to re-build with each revision of a design.
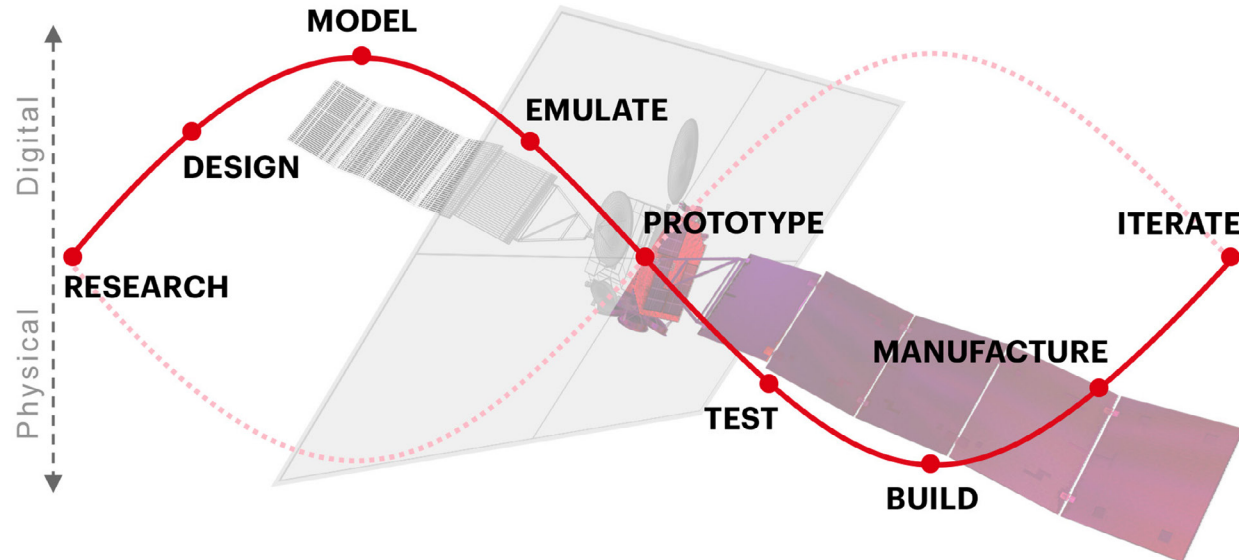

Figure 13. A digital twin development workflow

Network digital twins

Network digital twins are another major use case for digital twin technology in 6G. With disaggregation in 5G networks and more software-centric RAN, the continuous integration / continuous deployment workflow has become the goal that operators and integrators work toward for network management. With digital twins, networks can directly link the physical RAN measurements to upper-layer network applications and test new features and functionality in software environments before pushing them live.

Network digital twins enable engineers to integrate existing models or other digital twins into a system and conduct a trial without performing costly field tests. For example, modeling an existing network with varied channel conditions based on a new deployment or integrating non-terrestrial base stations into the architecture to provide coverage in design reduces the cost of launching high-altitude platforms or satellites. Coverage models can be simulated for planning, but those models can continue to iterate as coverage deploys and results from activities such as drive testing or site acceptance testing return from the field.
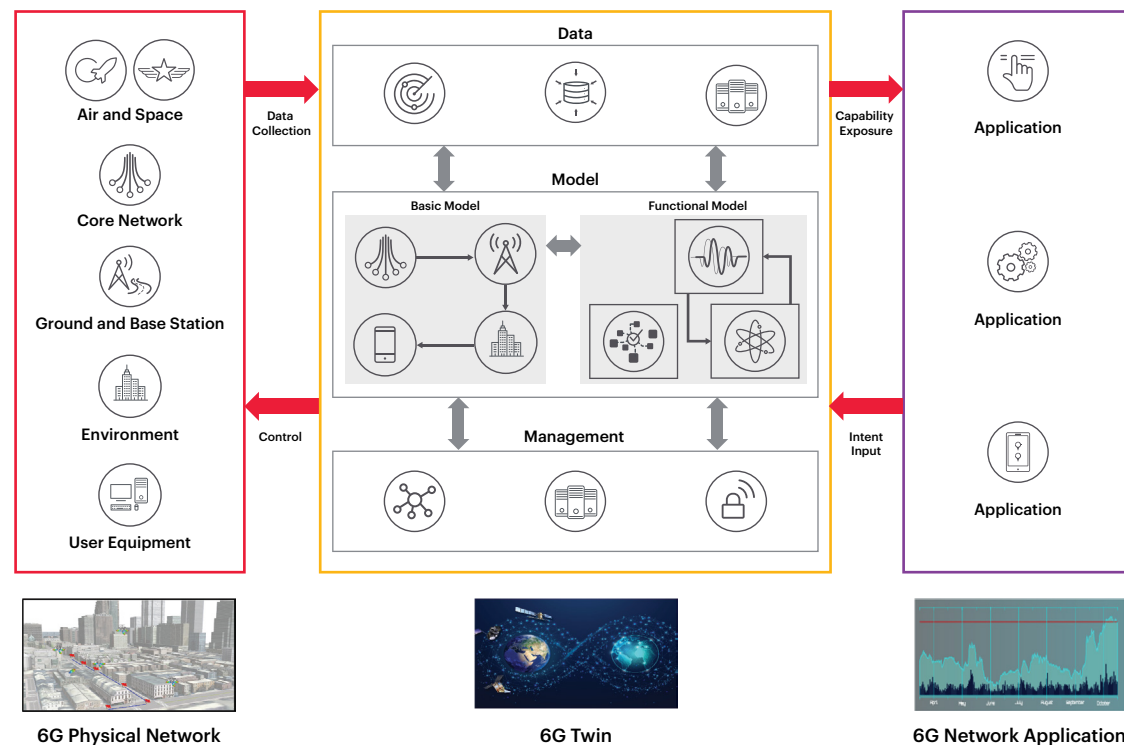

Figure 14. A reference 6G digital twin network architecture

Network digital twins can leverage circuit digital twins to evaluate performance gains by deploying at scale in the network digital twin environment. Evaluating a circuit digital twin in a larger network model helps engineers understand what happens when entire deployments upgrade to a new component or determine the minimum number of viable installations or upgrades required based on network performance.

Network digital twins are also valuable when evaluating cyberthreats and testing networks by simulating attacks. When running multiple attack vectors on a system in parallel, the digital twin can gather feedback on real-world behavior from the network and determine where vulnerabilities exist across various simulated threats. Network digital twins also offer the ability to review post-attack data showing the ripple effects of a cyberattack across the network. This type of information is highly valuable. Using digital twins allows you to acquire this data iteratively and swiftly across many simulations.

New network topologies

6G will rely on open, scalable, and virtual networks working together. To solve coverage challenges and bring these next-generation data rates to as many users as possible, many new network topologies must be considered for expanding access. Building on the software-centric RAN architectures used in 5G is one way to make networks easier to deploy and less costly, but that doesn't solve coverage issues in rural or remote locations.

Non-terrestrial networks covering various altitudes and regions may be one solution that brings 6G connectivity to every part of the world. But with these new network architectures come vulnerabilities that must be secured against digital threats. Cybersecurity for the networks of tomorrow is critical to maintaining service and ensuring the data of networks and users.

Virtualization, cloudification, and decentralization of the RAN

Since 2010, the RAN has evolved from distributed to centralized to virtualized to open and virtualized. Networks deployed before 2010 use a distributed RAN architecture in which the radio unit (RU) and baseband units (BBU) are located at each cell site and connected to the core via backhaul. Centralized RAN, sometimes called cloud RAN, created an option that further splits the RAN at the baseband level. The RLC, MAC, and limited parts of the upper PHY run on the distributed unit (DU), and a centralized unit (CU) processes the RRC and PDCP. Virtual RAN architectures virtualize DU and CU network functions on standard off-the-shelf x86 servers instead of using specialized hardware.

In recent years, the O-RAN Alliance has accelerated the trend toward virtual RAN architectures by creating well-defined, open interfaces between each RAN element. This process allows a network provider to choose different equipment vendors for different network elements. The architecture the O-RAN Alliance proposed pushes more of the physical-layer processing out of the RU and into the DU.

The O-RAN Alliance also promotes adding AI and ML into the RAN using a RAN Intelligent Controller (RIC). The RIC consists of real-time and non-real-time components that serve as a hosting platform that can run services for orchestration and optimization, automation, and management. Anyone can create applications that run on the RIC, called xApps and rApps. The RIC and its xApps and rApps are ideal places for AI and ML in a wireless network, and development work here is ongoing.

The trend of decentralization and virtualizing large parts of the RAN will continue in 6G and build on the concepts introduced in 5G and by the Open RAN movement. Any approach presents challenges, whether 6G RAN deployments use a single vendor or multiple vendors. Optimizing overall network performance can be more difficult when using hardware from multiple vendors rather than a single vendor, for example. But the ability to choose between different vendors to reduce equipment cost, for example, makes Open RAN compelling.
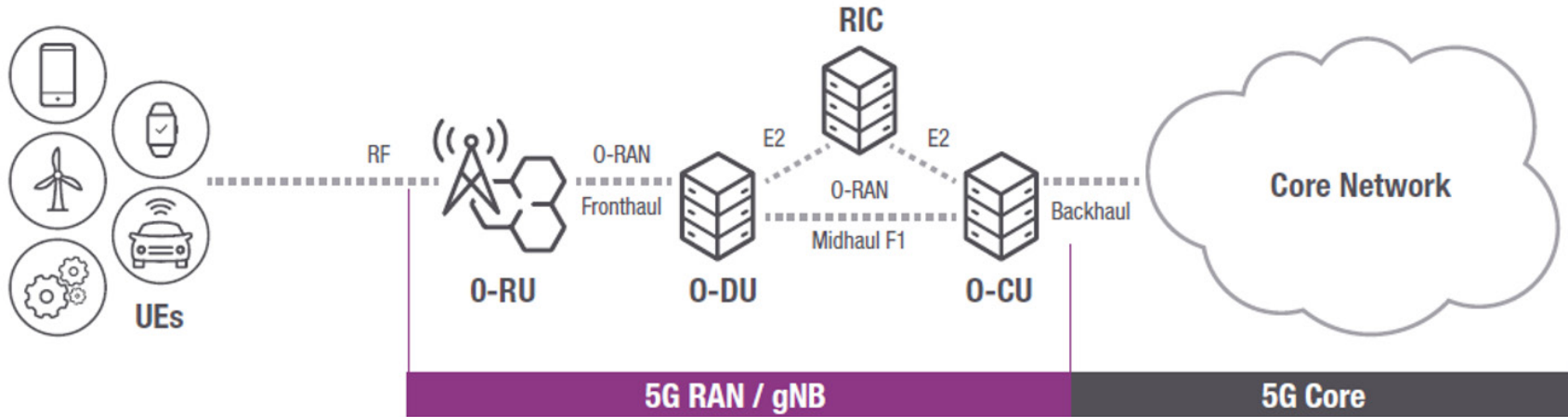

Figure 15. Open RAN architecture with UEs and core network

Virtualizing functionality will continue in 6G. Off-the-shelf servers can be less expensive to deploy than single-purpose hardware. Operators can sometimes move RAN functionality into the cloud, eliminating the need for dedicated hardware altogether. As more RAN functionality becomes virtualized, more opportunities are available to add artificial intelligence into wireless networks. Today, the RIC is one of the first places where AI is being added to the network. In 6G, AI will likely be in all parts of the RAN. Figure 16 shows a projected 6G network topology based on current trends.
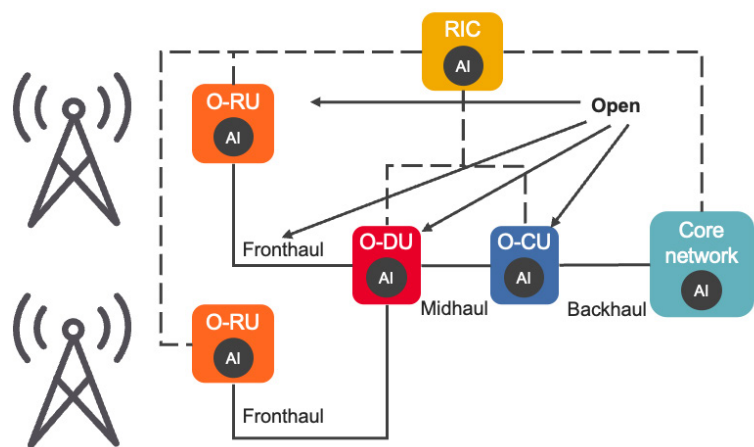

Figure 16. 6G network topology example

Non-terrestrial networks

Non-terrestrial networks (NTNs) operate using a gateway on the ground to enable ground base stations to communicate with aerial base stations. This setup can provide cellular coverage to rural areas or areas with rugged terrain where installing numerous base stations is difficult or too costly to justify. 5G has focused on two types of aerial base stations: low-Earth-orbit (LEO) satellite stations (orbiting at an elevation between 300 and 1,500 km) and high-altitude platform stations (HAPS), which fly at lower altitudes in the Earth's stratosphere.

LEO satellites deployed by companies like SpaceX have acted as more of an internet service provider than for cellular communications. Part of the reason relates to spectrum allocation, formalization of an NTN standard that is just beginning in earnest in Release 17, and deployment of satellites with the hardware required to work with handsets. It is possible that 6G handsets will include different transceivers to enable communication with LEO satellites, and time will tell if this use case prevails.

These challenges make HAPS more appealing. HAPS provides temporary coverage — for example, after a natural disaster. Therefore, regulatory approval for spectrum use and approval to use air space has not been a challenge. And by reusing cellular spectrum, HAPS can communicate with today's user equipment, providing another edge over LEO satellites.

HAPS does not come without challenges, though. Operating HAPS permanently will require regulations to allow it to work on cellular frequencies and fly in international airspace. More so than with other regulatory aspects of wireless communications, international agreements will be necessary for HAPS to align on topics like safety and unpiloted aerial vehicle operations.

With current technology, HAPS can operate for roughly six months. Improvement in solar panel efficiencies and batteries will be key to success. But since HAPS already runs on renewable energy and is hyper-focused on low-power operation, it also promises to be greener than other technologies.
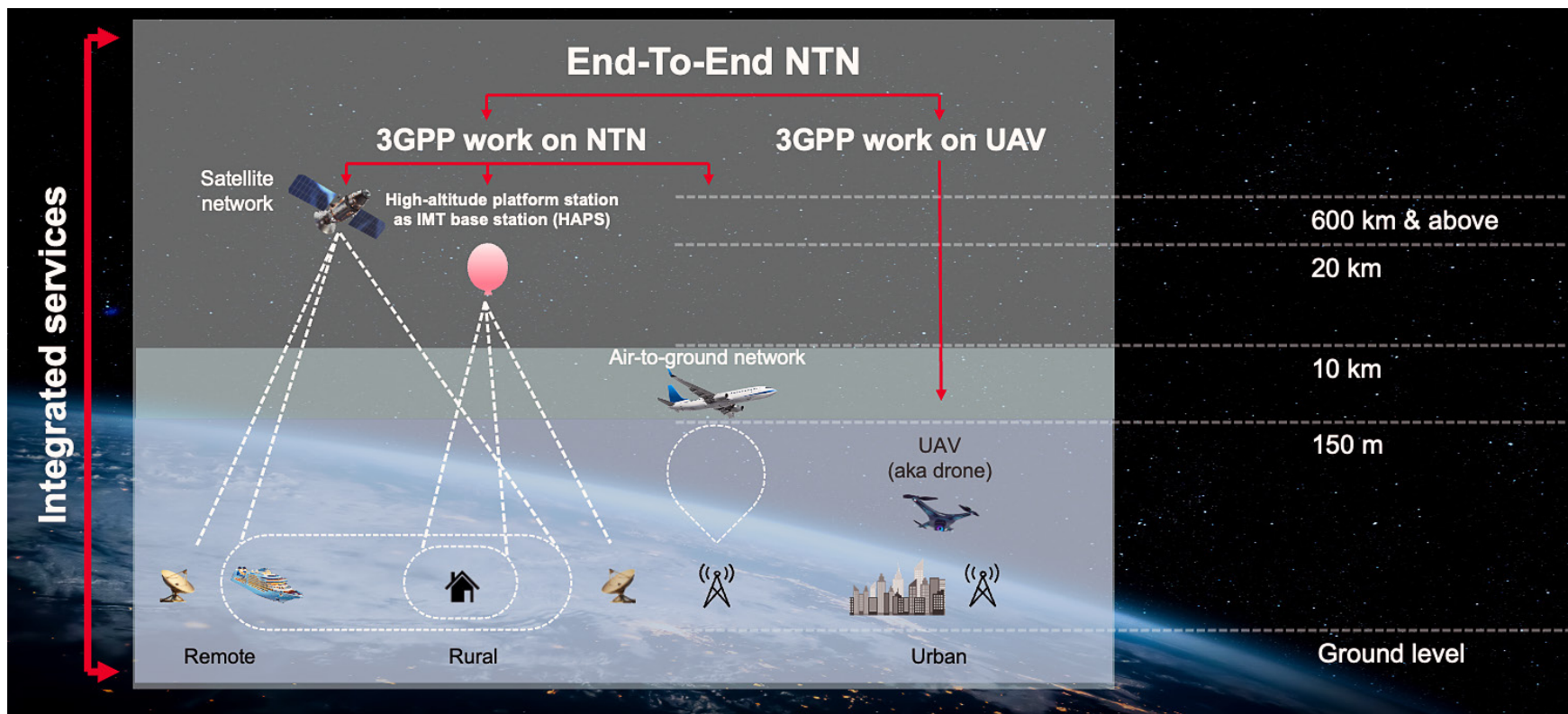

Figure 17. A conceptual overview of non-terrestrial networks

Security

As researchers and the industry move toward 6G technology, cybersecurity emerges as a pivotal field to ensure a future free of digital threats. Cyberattacks continue to grow, and successful breaches of organizations throughout the supply chain have increased. Third-party risks are a reality today.

This scenario is likely to keep happening as countries deploy 5G worldwide. 5G is the first technology to enable critical applications like e-health and smart cities, using ultra-reliable low-lantency and machine-to-machine communications. 5G marks the beginning of a revolution in network security design. 6G will continue this work, using hundreds of billions of new endpoints. While international standardization bodies have yet to standardize 6G technology, several areas of attention for future cybersecurity issues and threats are under discussion. We highlight some of the most mentioned.

Internet of Things and the attack surface

Each network supports a different number of connected devices per area simultaneously. Using the 4G network, you can connect up to 2,000 devices per square kilometer, or about 0.38 square miles. With 5G, that figure jumps to 1 million for the same range, and expectations for 6G are up to 10 million Internet of Things (IoT) devices in the same area.

The more connected machines, the greater the opportunities for cyberattacks on the network. Beyond phones, devices can include healthcare equipment, industrial machines, computers — anything connected to the internet and publicly exposed. This attack surface also includes the network infrastructure itself. As industry moves to 5G- and eventually 6G-powered networks, there will be billions of IoT machines. A radio access network will connect users to the cloud, core network, and a multi-vendor environment. All the components of this network infrastructure need to be reliable and secure against cyberattacks to support critical services.

One answer under development is called *cybersecurity by design*. This concept states that instead of finding answers for security threats after they happen, applications, services, and networks should be prepared to deal proactively with cybersecurity issues from the start, during the design of 6G-capable items. Regardless of their field, businesses will likely benefit the most from such an approach.

While cybersecurity by design is still a new mindset, companies can take measures today to prevent and deal with cyberthreats. For device manufacturers, employing a solution like a threat simulator in that live environment enables customers to run real-life scenarios with real-life malware in a safe environment. Through emulation, the team can not only find gaps and misconfigurations and remediate them but also practice security scenarios to validate techniques.

Zero-trust

In a 6G cybersecurity system, passwords will be a thing of the past. The cyber environment will be certificate-based and encrypted, meaning that 6G cybersecurity systems will check whether you are authorized to access a given software application, for example. 6G will also benefit from micro-segmentation, where the system can isolate communications, creating virtual "bubbles" and increasing security.

All these solutions will enable what experts call the zero-trust architecture that 6G cybersecurity demands. Zero-trust is a model that states that no entity is implicitly safe — the network cannot trust anyone who does not have the proper credentials. Such architecture promises to make communication and access to data much harder to invade.

Data here means much more than daily web browsing or even financial data. Imagine going to the hospital and undergoing a test. Technicians automatically upload the results to the hospital's servers. If the hospital suffers a cyberattack, however, your medical information belongs to hackers.

Enhanced fuzzing could provide a solution. Fuzzing is a cybersecurity testing technique in which a test device receives a message in a way that is different from what the system expects a secure message to look like. That raises a flag indicating that a cyberattack may be occurring, and security breaches can be identified in advance.

One of the challenges with fuzzing has always been that given the tens of thousands, if not millions, of messages and bytes you can have, the process can take a huge amount of time. Intelligent fuzzing looks to improve on these issues. A well-implemented specification gets uploaded to the test device — the coordinates to flag whether a message poses a possible threat. Then, researchers create a digital twin, enabling the team to make comparisons in real time. 6G should deliver this process in just a few hours, as opposed to the weeks it takes under today's 5G network.

Machine learning and artificial intelligence in cybersecurity

In 6G, AI and ML help train cybersecurity systems and algorithms. But they also offer a new layer of complexity on the cybersecurity side. The learning models themselves, not just the data used to train them, become vulnerable to cyberattacks. That will be especially true for new AI systems or approaches as the true extent of their behavior and capabilities develop over time, creating new vulnerabilities for hackers to explore. Attackers could also build their own malicious algorithms and learning models.

The good news is that solutions under development could prevent those problems before they start. Adversarial machine learning, an approach that teaches models how to identify a probable threat, is one way of shrinking the odds of a cyberattack. The idea is to feed the model with examples of corrupted information and train it to recognize threats autonomously. This is an area of active research that will continue to grow as 6G advances.

Conclusion

6G has the potential to shape the communications industry and push communications technology to make a societal impact through its sustainability and connectivity goals. Today, the 6G standard is in the early phases. Candidate technologies are being researched, prototyped, and simulated to see what directions the standard will take. Identifying the needs of the network and being able to predict what applications will be prevalent by 2030 is difficult, but the early stages help identify where the most fruitful focus will come from.

Research institutions and industry labs are working to design the simulations that will help them model the next-generation technology. Applying digital twin workflows to that simulation and pairing it with the prototype as it moves through the design phase opens up innovative ways to design and identify optimizations early. Modeling software tools that leverage as much real-world data as possible have the potential to solve major challenges early by taking in known insights from existing 5G deployments.

Research test beds will also be critical to success if 6G aims to spur collaboration alongside innovation. Connecting university research with industry expertise and government funding and direction means that test beds can be open and available for all researchers to contribute to.

6G covers a broad range of technologies with the aim of optimizing far more than just the RAN and the core. The ability to prototype new AI, digital twin, and software-defined tools across the wireless ecosystem will provide important results for applying those technologies wisely.

Fortunately, 6G does not have to be designed in the dark. By working with industry leaders in research and development, researchers can focus on the domains that need a push toward innovation. With any of 6G's boldest use cases, you will confront the tough question: How do we harness revolution and then make it real?

Keysight defines the best ways to quantify and verify performance across the wireless ecosystem. From RF to computing to cybersecurity, we pioneer the solutions you need to create the foundations of 6G. Extending our track record of collaboration in 5G and Open RAN, our 6G mission is clear: enable you and your lab to be bold, revolutionary, and first. 6G innovation starts here.

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