NOKIA BELL LABS

Envisioning a 6G future

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6G: The network behind the complete metaverse experience

When I say the word "metaverse," what comes to mind?

Do you think of donning a virtual-reality headset and escaping to a digitally generated 3D world? If you do, you are certainly not alone. The prevailing view of the metaverse today assumes that we will depart our physical surroundings and disappear into a virtual world to play, work and socialize. Digital immersion is a powerful vision for the metaverse, enabling countless potential applications for entertainment and productivity. But I would argue there is an even bigger metaverse out there just waiting to be explored.

The metaverse I am talking about is one where the physical, human and digital realities are conjoined. Through extended reality (XR), we can bring the metaverse wherever we go, rather than confine it to our homes and offices. This metaverse will be equally at home in the consumer, enterprise and industrial realms; and it will be built on the foundation of detailed digital twins mirroring our physical surroundings.

This grander metaverse fits squarely with Nokia's Tech Vision 2030, which has two main tenets. The first tenet is digital-physical fusion — our digital and physical lives will become inextricably linked. The second is human augmentation. That may sound like a scary phrase to some, but our view of augmentation isn't one of cyborgs and prosthetics. Rather it is a world where humans gain unprecedented insight into their health and lives and learn new ways to manipulate the physical world through digital means.

How do we achieve this vision? We will need ecosystem-wide innovation: new devices, software and tools; powerful compute capabilities and distributed processing; and technologies that can sense and understand the physical world and comprehend human action and intent. Underlying all these technologies, however, will be the fabric of connectivity. A powerful network is key to bringing the metaverse to life.

We have already laid the connectivity foundation with 5G, but as our networks become more powerful in the next decade so will the power of the metaverse.

We will make big strides when 5G-Advanced networks emerge in 2025, enabling true XR experiences, but when the 6G era begins in 2030, we will start realizing the metaverse's full potential.

In this book, my colleagues detail the key 6G technologies and trends that will shape this metaverse of the future. They explain how AI will predominate, how the network will be imbued with a digital sixth sense and how our systems will become trusted havens of privacy – just to name a few examples. You will learn not only how we view the network of the 6G era but also about the fundamental building blocks that will create it. Read on, and I will see you in the metaverse!

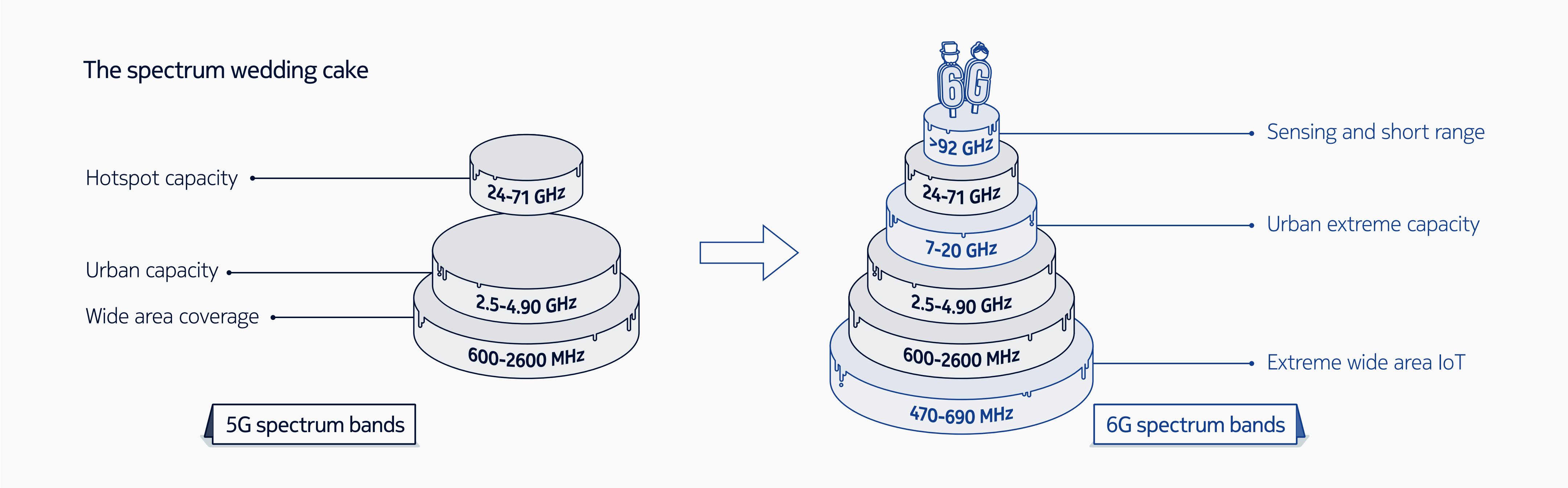
by Nishant Batra
Chief Strategy and Technology Officer, Nokia

01: The 6G era's enormous capacity demands will require new spectrum and extreme massive MIMO

By Harri Holma and Harish Viswanathan

Ever since the advent of language, communication has played a crucial role in the evolution of human society. Each major communications invention – writing, the printing press, the computer, digital media, the internet, social networks – has resulted in an exponential increase in the amount of information that humans generate, store and share. Today, the amount of knowledge in the world is doubling every 12 hours, and the real-time data from which new knowledge is extracted is growing even faster. All that data and knowledge is being transmitted through communication networks.

> “6G must be designed to provide, at minimum, 20 times more wide-area capacity than 5G.”



As a consequence, demands on our networks have grown astronomically, and nowhere have those pressures been more apparent than on mobile networks.

Traffic on mobile networks has increased by several orders of magnitude since inception of mobile data in 3G, and demand will only continue increasing in the future. To offer some perspective, a 35% year-over-year increase in demand would necessitate a 2000% increase in capacity over 10 years. Hence 6G must be designed to provide, at minimum, 20 times more wide-area capacity than 5G.

With advances in signal processing, radio technologies and computing, 6G will rise to meet this challenge through a combination of new spectrum, higher spectral efficiency and more spectrum reuse.

Exploiting the airwaves for 6G

Every generation of mobility has increased capacity by expanding carrier bandwidth – in essence creating a broader swathe of airwaves over which to transmit information. The move from 3G to 4G grew carrier size from 5 MHz to 20 MHz, while the transition from 4G to 5G saw carrier bandwidth grow from 20 MHz to 100 MHz. When 6G emerges, we expect spectral bandwidths to increase once again, reaching 400 MHz, greatly increasing the baseline capacity of a single cell.

To achieve these large carrier sizes, we’ll need to carve out large blocks of frequencies from previously untapped spectrum. As 5G has taken root, governments around the world have recognized the importance of advanced mobile networks for powering national economic growth, which has given them plenty of incentive to clear new spectrum for mobile use. We expect new spectrum bands between 7 GHz and 20 GHz to open up for 6G use, which will provide the necessary bandwidth to create these new high-capacity carriers.

This so-called mid-band 6G spectrum will become the workhorse frequencies of mobile networks. Lower bands do not have sufficiently large bandwidth allocations to create the 400 MHz carriers needed for 6G. Meanwhile the harsh signal propagation conditions in the ultra-high frequency bands make it expensive to use them for wide area coverage. Mid-band spectrum is the sweet spot for simultaneously providing extreme capacity and competitive coverage.

But these airwaves won’t be the only source of new spectrum for 6G networks. We expect governments to continue identifying new bands for mobile use, fueling the mobile broadband revolution further. In addition, it is likely we will see spectrum allocated for other types of use cases in the 6G era. For instance, regulators are looking at the 470-694 MHz band as a means for providing broad coverage in rural and remote regions. The low frequencies in this band mean signals propagate much further, extending the network’s reach. We may also see sub-THz bands beyond 90 GHz come into use, which could supply extremely high peak data rates for the most bandwidth-intensive applications as well as connect highly dense sensing networks.

Reusing airwaves to the utmost degree with extreme massive MIMO

New spectrum alone, however, isn't enough. Expanding carrier bandwidth from 100 MHz to 400 MHz gives us a 4X increase in capacity at most, well short of the 20X demand of the 6G era. We will need to utilize and re-use that spectrum in new ways.

The last several generations of mobility have seen spectral efficiency of wide area cells improve substantially mainly through the application of more sophisticated multiple-input multiple-output (MIMO) techniques. In short, we've added more antenna elements to each successive generation: 4G uses 2x2MIMO and 4x4MIMO while 5G benefits from massive MIMO using around 200 antenna elements and up to 64 transceivers. 6G may support on the order of 1024 antenna elements in the new mid-bands.

By moving into higher frequency bands we can support denser antenna arrays. As the 6G mid-bands are double the frequency of today's 3.5 GHz 5G bands, we can pack four times as many antennas onto an antenna array of comparable dimensions. These large antenna arrays will help achieve a significant increase in capacity by sending many more streams of data simultaneously.

Major steps in technology evolution are required to make these high-performance arrays possible. We will need new scalable, low-power radio-frequency and digital front ends, more sophisticated beamforming algorithms, and high-capacity fronthaul and baseband processing.

> "By moving into higher frequency bands we can support denser antenna arrays"

The 6G era's enormous capacity demands will require new spectrum and extreme massive MIMO

Scaling capacity by multiple factors

The math is simple. A 4X increase in spectrum multiplied by, say, a 5X increase in spectral efficiency will give us about 20X more capacity. While that equation may be simple, the innovation needed to achieve those numbers is not. Nokia Bell Labs is researching the underlying technologies to make those milestones possible in the 6G timeframe, starting with 5G-Advanced networks and culminating with the advanced signal processing, computing, optical networking and beamforming techniques that will give us this big leap in capacity.

A blanket of extreme capacity will be crucial as future applications will hunger for more bandwidth. 3D extended reality and dynamic 3D digital twinning, immersive digital world experiences and fiber-like fixed wireless access are among the more bandwidth-intensive applications that we can anticipate. And then there are the applications we aren't anticipating. Every generation of cellular communications has produced a big jump in capacity, and that hole has been invariably filled. 6G will be no exception.

> "Every generation of cellular communications has produced a big jump in capacity, and that hole has been invariably filled. 6G will be no exception"

02: In future networks, 6G radios will learn from one another

By Harish Viswanathan

The quest for artificial intelligence that mimics the amazing capabilities of the human brain began soon after the invention of the computer. After several cycles of exuberance and disappointment, we are now in the midst of an era in which machine learning is being broadly applied to substantially enhance the state of the art in a variety of different areas: image recognition and classification, natural language processing and robotic systems, to name just a few.

The beauty of artificial intelligence and machine learning (AI/ML) is that the basic approach of data-driven, trained systems easily extends to solving problems in multiple domains.

At Nokia Bell Labs we began wondering several years ago if we could apply those same problem-solving AI/ML techniques to wireless systems. What if we could engineer radios with the ability to adapt their signaling schemes and protocols to achieve the best performance for any given environment, in any given situation, unfettered by pre-defined parameters?

We've made good progress toward that goal, and we expect that a dynamic AI/ML-defined native air interface will be a key component of 6G networking in the future. This would at the very least revolutionize the way we standardize and productize wireless systems. But eventually these interfaces could give radios the ability to learn from one other and their environments. Rather than engineers telling network nodes of the network how they can communicate, those nodes could determine for themselves – choosing from millions of possible configurations – the best possible to way to communicate.

Embedding AI/ML deeper in the network

ML is not something completely new to wireless. For example, self-optimizing networks (SON) make extensive use of it. The SON approach to network management has always been based on applying traditional machine-learning techniques to large volumes of changing operational data to derive the most optimal network parameter settings over time. Meanwhile, deep learning is being applied to solve SON and radio resource management (RRM) problems, such as load balancing, carrier aggregation, handover optimization and anomaly detection.

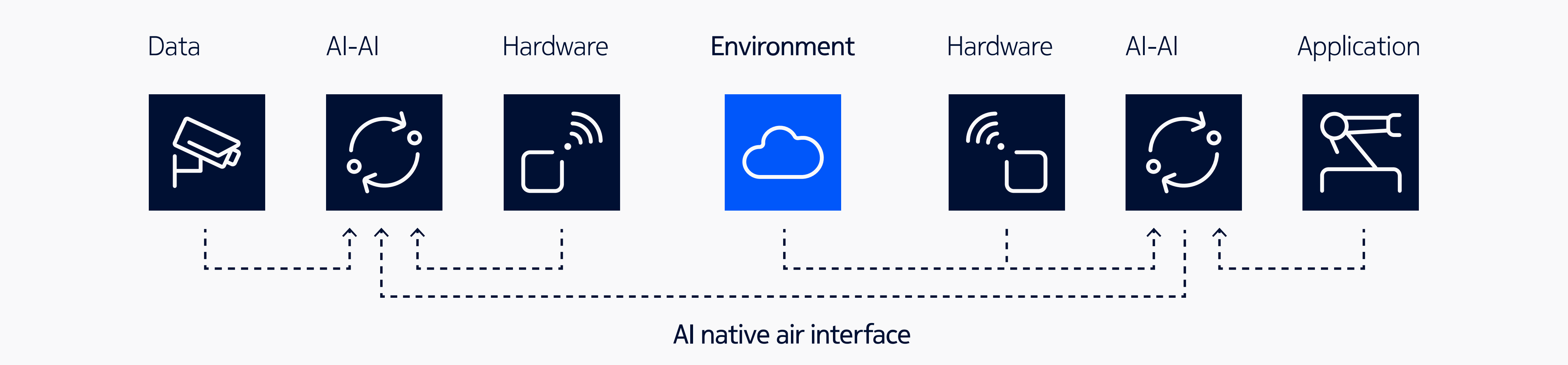
An AI/ML-based air interface would bring that intelligence much deeper into the network, applying it to real-time signal processing tasks in the transmitter and receiver. These are tasks traditionally solved through sound mathematical modeling driving near-optimal algorithms – techniques that have been perfected by human designers over five generations of mobile wireless systems. Signal transmission and reception is at the heart of these systems and has been steadily improving over time. But by introducing AI/ML to the process, we can push the boundaries even further to enable a self-optimizing air interface that is perfectly adapted to any channel, hardware and application sitting on top of it.

After a several years of investigating various applications of AI/ML to physical-layer and medium-access-layer (MAC) processing, we are beginning to see some promise. We have developed learned receiver blocks for 5G that consistently outperform traditional baselines. By jointly optimizing transmitter and receiver, we've seen additional throughput gains. And we've made rapid progress in ML hardware accelerators that will make native AI/ML air interfaces not only practical but also very energy efficient.

Even though wireless capacity is already close to the fundamental theoretical limits as defined by Bell Labs' own Claude Shannon, every expert in the field knows there is a big gap between real-world performance and theoretical performance. AI/ML may not be able to extend Shannon's Limit, but it could significantly bridge the gap between theory and reality by making the most efficient connection possible in any scenario.

First, it could dynamically learn and set up bespoke waveforms, constellations, and pilot signals that make more efficient use of available spectrum, resulting in better performance in certain scenarios such as higher mobility MIMO transmissions.

Second, on the MAC layer, AI/ML could customize signaling and access schemes, which could, for example, seamlessly switch between contention-based or scheduled access adapting to the service needs automatically. Third, a learned air interface could embrace hardware non-linearities and limitations and fully adapt to them whatever the target platform is. Fourth, AI/ML could choose among all the myriad of parameters in a radio network in ways no human can optimally accomplish.



> "What if we could engineer radios with the ability to adapt their signaling schemes and protocols to achieve the best performance for any given environment?"

What does this mean for future 6G networks?

It means that networks could eventually adapt to any data source, application or use case. This flexibility would be particularly powerful in private networks, such as industrial communications systems. The radios in a factory, for instance, might be configured to support industrial sensors at one moment, but in the next they could reconfigure to support robotic orchestration or video surveillance – moving to different spectrum bands, reconfiguring the number of signal paths and changing modulation schemes as the specific application demands. What's more, by learning from their environments, those radios could adapt to millions of different scenarios that engineers might not anticipate. Even if they could define every single one of those scenarios, the industry can't standardize millions of different configurations. A flexible interface that auto-adapts could very well change the face of network optimization.

Finally, a learned AI/ML air interface could transform how R&D is done. If we can truly implement all transmitter and receiver signal processing functions through machine learning, then we can fundamentally alter the way algorithms are designed. Instead of separating the receiver functions into multiple separate algorithms, each of which is then implemented as software on special purpose hardware, design would focus on partitioning functions and selecting the best machine learning model architectures for each function. The subsequent implementation on hardware as well as training would be significantly automated using various tools.

> "A flexible interface that auto-adapts could very well change the face of network optimization"

The larger 6G context

In the 6G era, the inexorable demand for higher performance and higher capacities will require exploiting ever-higher bands, wider bandwidth signals, new solutions for joint communication and sensing, and new approaches to security and trust. We feel that the AI/ML-based air-interface could be a transformative element of these future 6G networks.

These technologies will encourage a 6G design that is not only optimized for communication but also to help its users perceive and understand the physical world, thus augmenting human abilities in the most intuitive ways. To achieve that goal, we will need to take advantage of every tool at our disposal, so it only makes sense that we exploit the rapid advances in AI/ML to create the most flexible, adaptive networks possible.

"These technologies will encourage a 6G design that is not only optimized for communication but also to help its users perceive and understand the physical world, thus augmenting human abilities in the most intuitive ways"

03: Building a network with a sixth sense

By Thorsten Wild and Harish Viswanathan

Imagine a wireless communications system becoming aware of its environment, of the people and objects in its coverage area, without any active sensors or communicating devices present - essentially a network that is also able to sense.

Sensing is fundamental to being a human, but while our senses are powerful, they are limited to our immediate vicinities.

We must be present to sense temperature, pressure, weight or other physical parameters. We must be within a few hundred feet of the sound source to hear, and at best we can see only large objects a few hundred meters away. If we, however, give our networks the ability to sense, then our awareness is no longer limited to our surroundings. The network becomes our sixth sense.

In this network, radio signals transmitted by base stations and user devices don't just carry data. Those wireless propagation channels also become a source of situational information. The network can compare received signals reflected off objects against their original transmissions to gather information about those objects. Those received signals can tell us not just about the presence of an object, but it can determine its type and shape, its relative location and velocity, and even its material properties.

As wireless communication networks are ubiquitous, a "mirror" or digital twin of the physical world can be created using network sensing. By interacting with this digital twin, we could extend our senses to every point the network touches. We could avoid traffic accidents by sensing unseen cars driving around a corner. We could interact directly with machines and robots remotely, seeing what they see, hearing what they hear, while directing their actions through simple hand gestures captured by the network. The new applications for this kind of network sixth sense are limited only by our imaginations.

> "If we give our networks the ability to sense, then our awareness is no longer limited to our surroundings. The network becomes our sixth sense"

A natural evolution

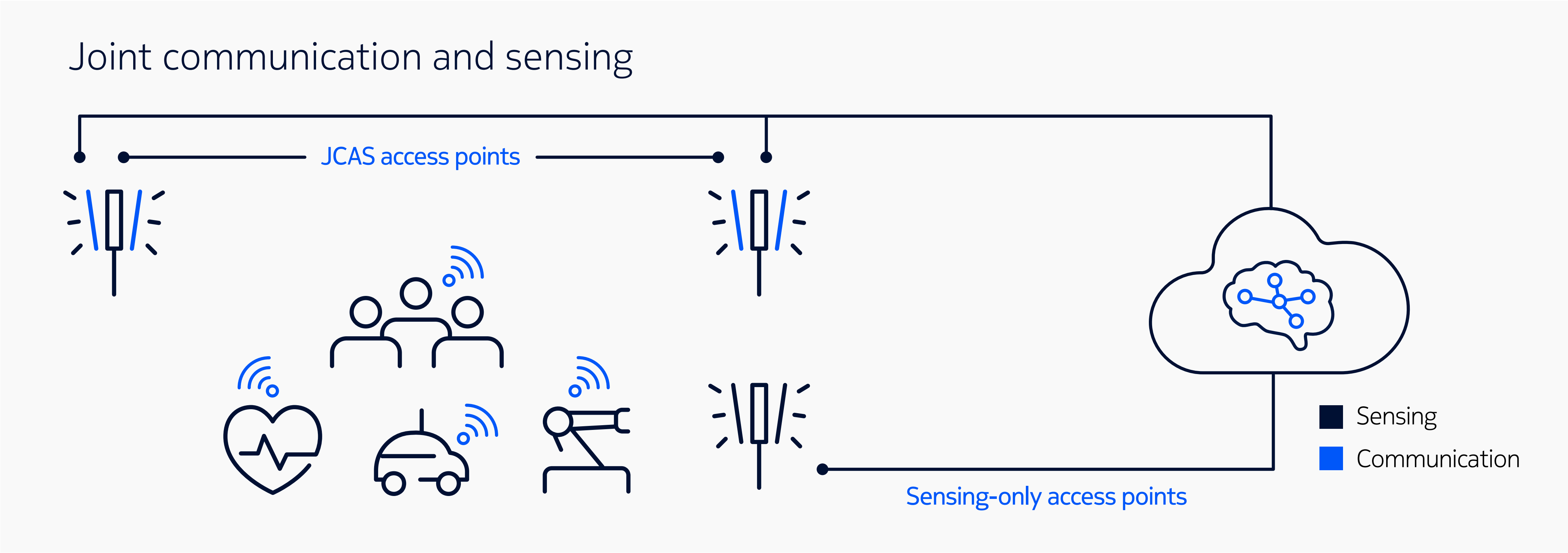
The quest to augment our sensing with machines is as old as history. Think about the mouse trap – it senses the presence of a mouse when you are not there. Or the telescope that augments your vision to see the stars. More recently, the internet of things hosts billions of networked sensing devices that can extend the reach of the human senses far beyond their biological limits.

Radio signals have been a key part of the sensing infrastructure since James Maxwell in the 19th century first established that radio waves can be reflected off objects. Radar was first used to "see" ships in the fog, and from that point on, radio signals have been used extensively for numerous sensing applications such as navigation, ranging and object detection. In fact, it was the Nobel Prize-winning radio astronomy work at Bell Labs that established that the universe began with the Big Bang, allowing humans to sense what happened 14 billion years ago!

The logical next step is to extend these radio sensing capabilities beyond specialized machines and applications and place them in every cell and node of the wireless communication infrastructure that surrounds us today.

5G already supports radio-access-technology-based localization, but the current standards do not yet offer the in-built capability to detect objects not connected to the network. Such an integrated sensing capability will be natively designed into 6G, allowing sensing to be offered as a service right alongside communications.

The move to 5G made broader spectral bandwidths and higher frequency bands available, and the move to 6G will allow networks to climb into higher frequencies and even wider channels, which will be key to enabling sensing. Higher spectral bandwidths provide better range resolution as propagation conditions become more "geometrical" in nature. With these bigger bandwidths, the network will perceive radio frequency reflections as images similar to the visual images humans perceive with their eyes. Thus objects can be more easily and more accurately detected by a 6G network.



A new world of sixth-sense applications

This sensing network would open the door for a plethora of new services. In outdoor environments, the network could detect the location, speed and trajectory of all vehicles and pedestrians in an area, issuing warnings if any of their paths are about to intersect. Or the network could simply search the block for empty parking spots.

At work or at home, the network could detect if a vulnerable person has fallen and even “hear” their heartbeat, alerting emergency responders about possible trauma. Factories could use network sensing to allow humans and industrial robots to work side-by-side on the shop floor in perfect safety. End consumers could communicate with gestures to appliances, devices and robotic assistants, while those same visual cues could be used to communicate with the network itself. Virtual reality would greatly benefit as complicated input rigs would no longer be required to manipulate the digital world. The network would detect the motion of a hand or a leg – or even an eyelid – transmitting those cues to the VR simulation.

In many cases, network sensing would be used to complement other sensing technologies. Camera and network sensing data could be fused together to detect objects in smoke, fog, dust and darkness.

Network sensing could also be used in places where, for privacy reasons, cameras aren’t allowed. Radio Frequency (RF) sensing is less intrusive than video surveillance as radio signals already permeate our surroundings. For that same reason, network sensing is also perfectly safe. Network sensing won’t inundate the world with new radio waves. It will simply measure the properties of the signals already being used to transmit data across the network.

Finally, these radio sensors would transform how we optimize the communication network. A network more aware of its surroundings can anticipate factors that could lead to degradation of performance or interruption of service. For instance, the network could sense an arriving truck intersecting with a beam’s path. It could then send out new beams or change transmit points to ensure service isn’t affected.

> “A network more aware of its surroundings can anticipate factors that could lead to degradation of performance or interruption of service”

A new mobile revolution

Mobile networks have transformed almost all lives on the planet by allowing us to communicate from anywhere. Sensing-enabled mobile infrastructure could create a new revolution by extending our awareness beyond our immediate surroundings without the need for new sensing devices.

Creating this sixth sense will require more than just network-as-a-sensor technology. A myriad of other systems from AI/ML to digital twinning to new software and knowledge systems will be needed to interpret what the networks see and build the applications and services that will act upon that data.

In the 6G era, the inexorable demand for higher performance and higher capacities will require exploiting ever-higher bands, wider bandwidth signals, new solutions for joint communication and sensing, and new approaches to security and trust. These technologies will encourage a 6G design that is not only optimized for communication but also to help its users perceive and understand the physical world, thus augmenting human abilities in the most intuitive ways.

"Sensing-enabled mobile infrastructure could create a new revolution by extending our awareness beyond our immediate surroundings without the need for new sensing devices"

04: How 6G could replace wires in life critical communications

By Paolo Baracca and Gilberto Berardinelli

5G has done a tremendous job in improving reliability of wireless communication for a plethora of applications and services, but there is still work to be done before 5G can replace the inflexible, yet trustworthy, cable for all services.

We use wireless connections for streaming, video calls and downloading big files because we accept the fact that our connections may suddenly drop or become intermittent.

But for life-critical services such interruptions are intolerable. When it comes to engine control in vehicles, hazard prevention in factories or flight stability control in aircraft, the cable remains the gold standard for connectivity.

We believe, however, 6G will make it possible to eliminate wired communication entirely, at least for short-range transmission. In our 6G research, we are exploring how wireless can be used as an invisible cable, achieving the same level of latency and reliability as dedicated wires. This can unleash new possibilities for wireless communication such as replacing the highly sensitive internal networks in vehicles while maintaining the same service levels, lowering vehicle weight and reducing maintenance costs. A 6G network could enable flexible modular robots in an industrial IoT scenario. It could even keep our hearts beating and our limbs moving by providing the critical link in healthcare applications such as cardiac pacing or muscle control for disabled patients.

What's in in-X?

In our 6G vision, all highly sensitive connectivity should be in-X, meaning it is provided by highly specialized radio cells installed within the entity where the application runs, for instance in robots, production modules, vehicles and even human bodies.

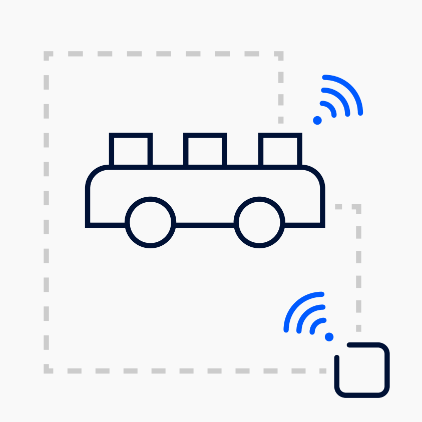
We say subnetwork, because these specialized radio cells must be able to operate autonomously even when out of coverage of an overlay wide area network. These cells support life-critical services that cannot depend on connections to the overlay network, though they can benefit when those connections are available.

> "6G will make it possible to eliminate wired communication entirely, at least for short-range transmission"

Examples of in-X subnetworks

In-production module

In-robot



In-vehicle

In-body

In-house

The possibilities for subnetworks are huge, but so are the challenges. Wireless is a shared medium, prone to detrimental effects such as fading, noise and interference – all of which could compromise the integrity of a subnetwork connection.

Spectrum is key

How can 6G support extreme connectivity requirements, which can demand loop cycles below 100 microseconds, more than six nines reliability or multi-gigabit data rates? The key is radio spectrum. A very large amount of spectrum is needed for making the in-X concept a reality because more spectral bandwidth allows for more robust connections, which in turn provide higher fault tolerances.

If a sufficiently large spectrum block is not available for an in-X subnetwork installed in a vehicle driving on the highway, for example, some of the sensors may stop working or may be forced to cope with intolerable delays. This may cause a slow vehicle response to hazards and possibly compromise the life of the drivers and passengers.

In general, spectrum below 10 GHz provides good propagation conditions for in-X subnetworks. Radio waves in this frequency range can easily travel through obstacles and therefore support reliable communications even in non-line-of-sight conditions between transmitter and receiver.
For example, a sensor in a vehicle can reliably communicate with a controller even if the radio path is obstructed by the engine. However, this spectrum is largely occupied by other radio technologies (radar, satellite, cellular). That currently makes it impossible to accommodate subnetworks unless a large amount of spectrum is rededicated for their use.

One alternative, however, would be to operate underlay networks in the sub-10 GHz bands specifically for subnetworks, using a similar approach to ultra-wideband (UWB). Since their very short range allows these transmissions to operate at very low power, in-X transmissions would be mere whispers passing discretely between in-X devices under the “louder” networks operating in those bands. This could permit in-X subnets to co-exist with cellular, satellite and other wireless technologies.

Another possibility is to look to the higher frequencies, for instance 26-28 GHz millimeter waves. In this case, we have the opposite problem of sub-10 GHz: There is a large block of spectrum available, but propagation conditions are more complicated. Such frequencies are more sensitive to obstacles and blockage effects. We could eventually overcome those blockages through macro-diversity, deploying multiple antennas in the subnetwork area.

Finally, unlicensed spectrum has a role to play in subnetworks. We foresee future greenfield unlicensed spectra allocated to subnetworks, where new regulatory rules are tailored to their specific requirements and traffic types while still ensuring fairness among devices.

“Communications to support life-critical services must be proactive, following an act-before-fail approach”

A proactive radio

Traditional radio systems are inherently reactive, meaning they measure the current radio signal quality and connectivity performance, and then adapt their communication parameters (transmit power, data rates, frequency bands) accordingly.

Traditional systems are therefore allowed to fail and try again. For example, upon a failing to transmit a packet, a device would retransmit the same packet until it succeeded, possibly allocating more radio resources to each retransmission to make them more robust.

An act-after-fail approach, however, is unsustainable for life-critical in-X services. For instance, an anti-lock braking system can’t tolerate multiple – or even single – failed transmissions in an in-vehicle subnetwork commanding it to engage. Communications to support life-critical services must be proactive, following an act-before-fail approach. For example, instead of transmitting a packet only once and waiting for an acknowledgement, an in-X device would transmit the same packet multiple times simultaneously. The subnet could also transmit that packet over several different frequencies. Even if one or several of those duplicate packets failed to arrive, the extreme redundancy of the in-X design means the transmission would ultimately be received.

The challenge of interference

In-X deployments can lead to very dense scenarios, such as vehicles in a congested road or people attending crowded events. As radio spectrum allocated to in-X subnetworks would be finite, neighboring subnetworks may end up operating over the same frequencies creating high levels of interference. A smart radio resource management is therefore needed for counteracting such interference and ensuring life-critical services in all conditions.

Moreover, we need to ensure subnetworks are robust enough to resist non-cellular interference. Someone trying to create havoc with critical systems could try to jam in-X systems by flooding the airwaves with noise, preventing subnetworks from transmitting. Any subnetwork must be able to fend off these kinds of malicious attacks.

When subnetworks are connected to an overlay wide area network, a central controller can manage the radio resources shared among neighboring subnetworks, minimizing mutual interference. Such centralized approaches are more efficient than distributed ones but depend on connectivity to the external network. They therefore may only be possible in controlled deployments, for instance robots in a factory.

Since life-critical services cannot rely on a possibly intermittent connection to an external network, distributed solutions for interference management should also be in place. In a distributed solution, each subnetwork decides the frequency resources it will use by measuring local conditions. Here artificial intelligence techniques such as reinforcement learning could play a key role.

The 6G era won't be a world completely devoid of wires, but we will increasingly turn to wireless solutions to solve the final pieces of the connectivity puzzle. We believe that extremely fast and reliable short-range communications will become a critical enabling feature of the era.

> "We believe that extremely fast and reliable short-range communications will become a critical enabling feature of the era"

05: A new architecture for a new 6G era

By Gerald Kunzmann

Speed, capacity, latency – for generations, networks and services have been measured by these and other traditional key performance indicators (KPIs). As we start our journey to the 6G era, however, additional KPIs will become important.

We will see new performance measures that reflect the broader goals of multiple stakeholders

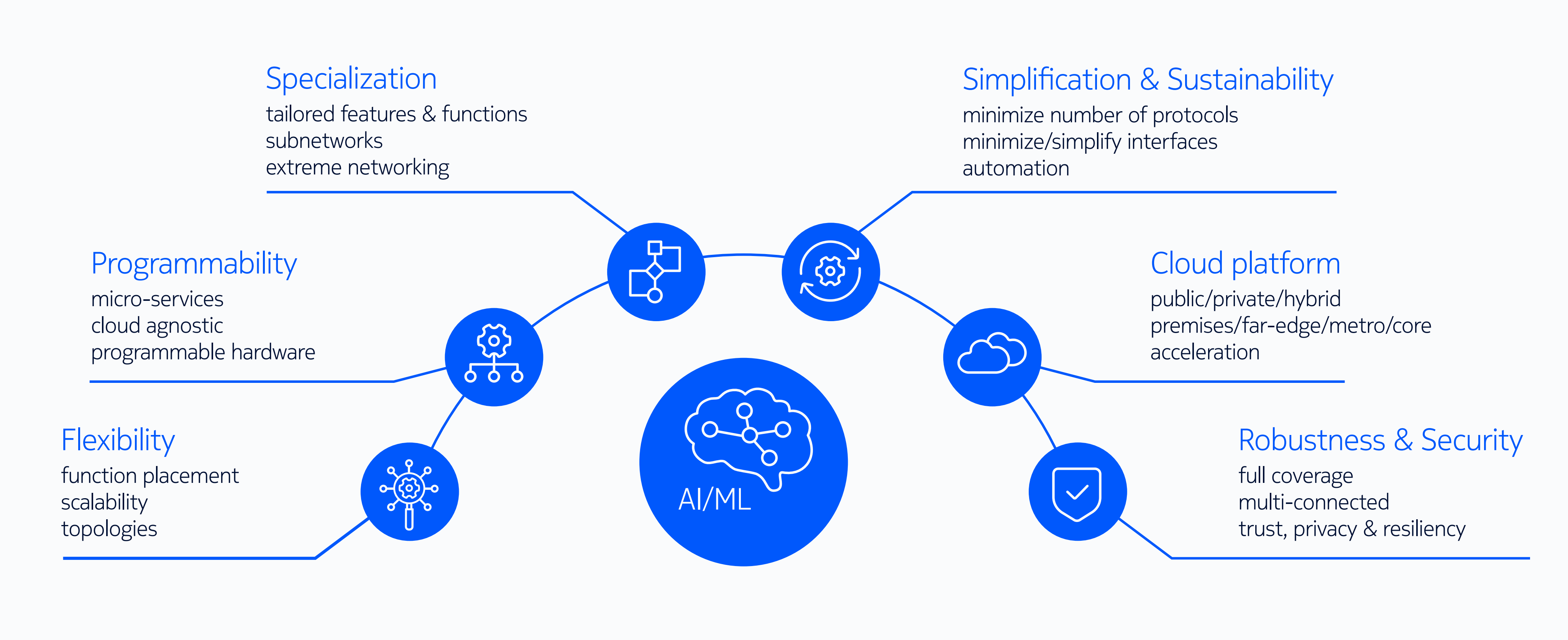
These include operators, webscalers, enterprises, neutral hosts and industry, which in turn reflect the values of society.

Metrics like sustainability, openness, digital inclusion, privacy and trust are becoming additional means by which we measure the capabilities of networks and services. These are the types of new key value indicators (KVIs) that will become just as important – if not more important – than the traditional KPIs of speed, capacity and latency. To build operational networks that maximize these new KVIs, we must have a fresh design approach for the 6G architecture blueprint.

> "As we fuse the human, digital and physical worlds in the 6G era, a wave of new devices will become part of our connectivity fabric, linking every manner of wearable and personalized sensor"

New architecture goals

At Nokia we envision a new 6G system architecture with the following distinct design criteria or goals in mind: cloud platform, simplification and sustainability, flexibility, programmability, specialization, robustness and security, and native integration of AI/ML capabilities.



All those design criteria and goals need to be considered when the new 6G system architecture is being developed, while individual actors in the value mesh may have different priorities based on the use cases they are targeting.

All stakeholders will need to focus on sustainability by creating zero-carbon-footprint networks where every aspect of the network's operation is designed to minimize or offset CO_2 emissions. Other stakeholders might choose to specialize their networks for the metaverse, enabling immersive experiences like extended reality (XR), holographic telepresence and digital twinning. Or an enterprise might build a network focused on connecting the growing multitude of low-power devices and sensors, which requires tailored features and functions. As we fuse the human, digital and physical worlds in the 6G era, a wave of new devices will become part of our connectivity fabric, linking every manner of wearable and personalized sensor – even the fabric in our clothing itself. Such highly interconnected systems will need specific attention to privacy and security along with the data they exchange and generate.

The 6G system architecture

Building a network that supports these kinds of use cases and system goals will require various architectural innovations that span multiple areas. A 6G network can spread across multiple heterogenous and distributed public and private cloud platforms from different stakeholders and will utilize a cloud platform with varying capabilities such as hardware acceleration. Implementations will achieve a new level of programmability to meet the demands of numerous and diverse use cases.
The architecture will come with the flexibility and the high degree of specialization necessary for it to be deployed in large-scale wide area networks as well as in extremely local on-premise and personal-area networks. 6G will support that degree of customization to the most granular degree, making each network unique and tailored to its intended deployment needs.

To achieve this new flexibility in network design, we are exploring the system architecture of the 6G network in a fresh manner. In short, we are starting over, abandoning our ingrained prejudices about the current architecture design while giving ourselves the full freedom to innovate a new architecture design.

First, we assume fully cloud-native network functions and services that can be flexibly and dynamically placed anywhere to achieve a wide variety of latency targets and other requirements.

Second, we will introduce a new level of specialization and simplification that will allow mobile networks and services to be built almost like Lego sets with each radio access network (RAN) or core network function comprising a “brick.” Open and service-based interfaces will allow customers to easily assemble these bricks, integrating services and functions from multiple vendors depending on the customer's specific needs and conditions. For instance, we could start with a primary structure consisting of authentication and subscriber identification bricks and then stack secondary bricks like mobility, interworking and roaming on top. We could finish the construction with architectural details and add-ons such as specialized functions and tailored features.

In the process, the distinction between access network and core network will blur, allowing for a more direct communication between RAN and core network functions. Although the concepts of RAN and core network won’t disappear entirely, we can enrich interactions between the two, collocate functions and even merge similar functions.

The 6G architecture will come with advanced domain automation functionalities providing orchestration and automation across multiple network domains, possibly spanning multiple stakeholders, multiple administrative domains and additional resources in the far edge and on premises beyond the traditional mobile network.
A significant increase in compute and storage capabilities, for example, is required to store and process the massive amount of data to be collected for services like AI/ML, extended reality (XR) and the metaverse. A dedicated data and information architecture is being proposed to collect and expose the required information from the various data sources across the whole 6G system in an efficient manner. Also, it is crucial to determine the optimal placement and selection of those resources and services from an overall system performance perspective, while respecting service constraints and system KPIs/KVIs.

> “We are starting over, abandoning our ingrained prejudices about the current architecture design while giving ourselves the full freedom to innovate a new architecture design”

A new way of deploying networks

Nokia has already started taking the first steps towards enhancing the network capabilities with a range of new features and enhancements in 5G-Advanced, which will be launched in the 2025 timeframe.

As outlined by our Chief Strategy and Technology Officer Nishant Batra in a recent blog post, Nokia has begun looking differently at the way it crafts networks. Nokia will design networks as more than a long list of features, enhancements and technologies, providing service providers with the means to enhance network capabilities in four dimensions: experience, expansion, extension and operational excellence. The new 6G system architecture is the next logical step in that migration path exploiting the full potential of recent innovations and proven concepts. It will act as the glue and fabric for these technologies, giving us the foundation to make more radical changes to the way we craft networks.

> "The new 6G system architecture is the next logical step in that migration path exploiting the full potential of recent innovations and proven concepts"

06: Trust thy 6G network: The future of communications hinges on security and privacy

By Volker Ziegler and Michael Montag

In the 6G era we will need to put far more trust in the network than we do today. In the 2030s, we will immerse ourselves in new digital worlds, utilizing holographic telepresence to brainstorm with our colleagues and experience intimate moments with our families halfway across a city – or even across the world. We will have a wealth of robots at our disposal. Highly orchestrated multi-robot systems will revolutionize industry, but collaborative robots will also spread to everyday life, for instance helping to care for the elderly or the infirm at their homes. Augmented intelligence in conjunction with body-area networks will monitor our biochemistry, warning us of potential health problems long before we experience symptoms.

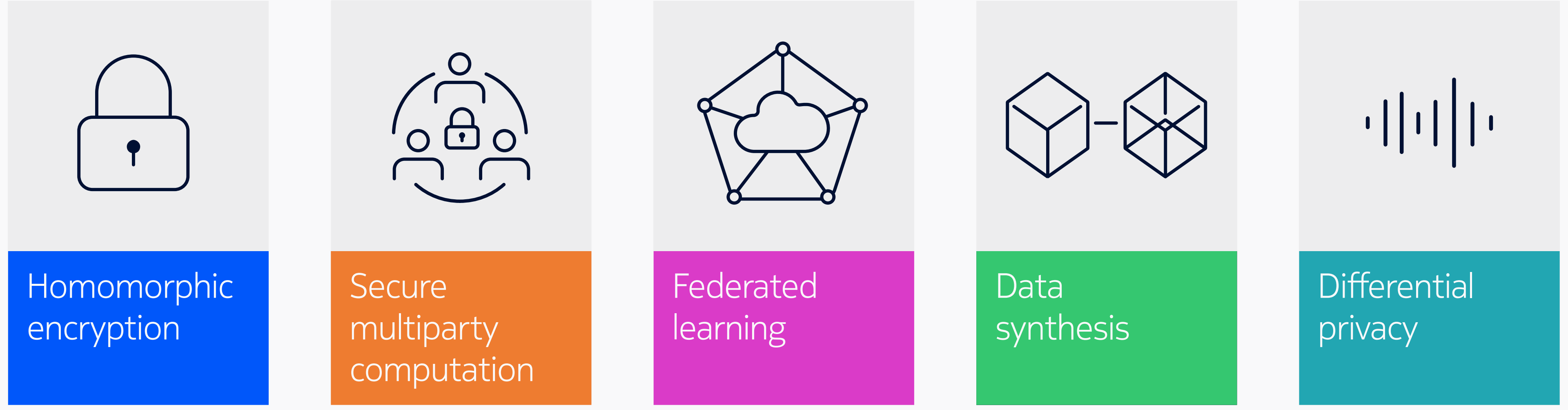
These disparate scenarios have two things in common.

First, they will be fueled by 6G networks. Second, all these use cases will require new levels of security, cyber-resilience, privacy and trust. We will need to know that our extended reality meetings and conversations are private, that our robot systems are secure and that our most personal health data is protected.

Solving and proactively tackling the challenge of security, privacy and trust will be key unlocking the full value potential of 6G era communications. At the same time, the threat of malicious attacks will expand due to the proliferation of billions of devices and sensors and millions of subnetworks that typically reside in untrusted domains. As our networks evolve for the future, aspects of that transformation will contribute to growth of that threat vector in multiple dimensions, for instance through open interfaces and architectural disaggregation, the mingling of open-source and multivendor software, and multi-stakeholder supply chains. Moreover, in the 2030s artificial intelligence and machine learning will play a much larger role, for good and bad. While AI/ML will benefit 6G security immensely, we're also likely to see many AI-initiated attacks as well as attacks directed against the vulnerabilities of AI/ML-based mechanisms in our networks.

What we need is a comprehensive set of security technology enablers for the 6G era, enhanced and supported by AI/ML and new principles of cyber-resilience. We require a new paradigm for the way we create software. Software generation will need to become fully automated. Those automation tools will include static and dynamic bug detection, code optimization and automated code testing. Experimental and continuous in-production fault injection for testing purposes will likely become the norm, assuring cyber-resilience in the 6G era. And just as important, automated, distributed, cognitive closed-loop security operations need to be part of our 6G security vision.

Anonymization and privacy-preserving technologies



Privacy will become paramount

In the 6G era, the network and its services will continuously generate, store and process massive amounts of data. Digital breaches in the 2030s could expose far more than credit card numbers and confidential business messages. As the 6G network becomes our digital sixth sense, it will become capable of determining a person's precise position within a room, as well as tracking and predicting their habits. As 6G biosensing emerges, the network may know our most intimate health details in order to monitor our medical conditions and medication levels or even warn us of an imminent heart attack or epileptic seizure. However, this data could be used for increasingly sophisticated fraud, blackmail and extortion attempts. It could be used by unscrupulous businesses to target potential customers based on their most intimate preferences and fears. And it could be used by governments to monitor their citizens.

Similarly, the confidentiality of business data will assume even greater importance. Many business cases today are founded on the controlled access to and ownership of customer, process and business data, and those cases will become the norm. This opens businesses up to ransomware attacks by denying access to data or for corporate espionage. "Deep fakes" in the virtual world of the 2030s will pose tremendous challenge and risk.

So how can we reap the benefits of advanced health monitoring without falling victim to malicious data appropriation? How can we fully digitalize our businesses without opening ourselves to relentless attacks? We will need anonymization and privacy-preserving technologies that strike a balance between minimal data exposure and legitimate analytics.

Those technologies will include homomorphic encryption, which permits us to analyze encrypted data while yielding the same encrypted results as if the analysis were conducted on plain data.

They will include secure multi-party computation that doesn't disclose internal data. They will include distributed storage and processing at edge and central data centers along with federated learning approaches. We will also need to develop techniques that transform raw data into a form of synthetic data that maintains characteristics necessary for analytics but discards or secures characteristics that are irrelevant or private. All of these will be built on technologies that attest data integrity, provenance and ownership. Trust technologies like Trusted Platform Module and Trusted Execution Environments will protect data integrity and provide proof of data ownership anchored in silicon and hardware. Blockchain technology will continue to support distributed data brokerage by securely tracking data access rights.

> "What we need is a comprehensive set of security technology enablers for the 6G era, enhanced and supported by AI/ML and new principles of cyber-resilience"

The need for quantum safe security

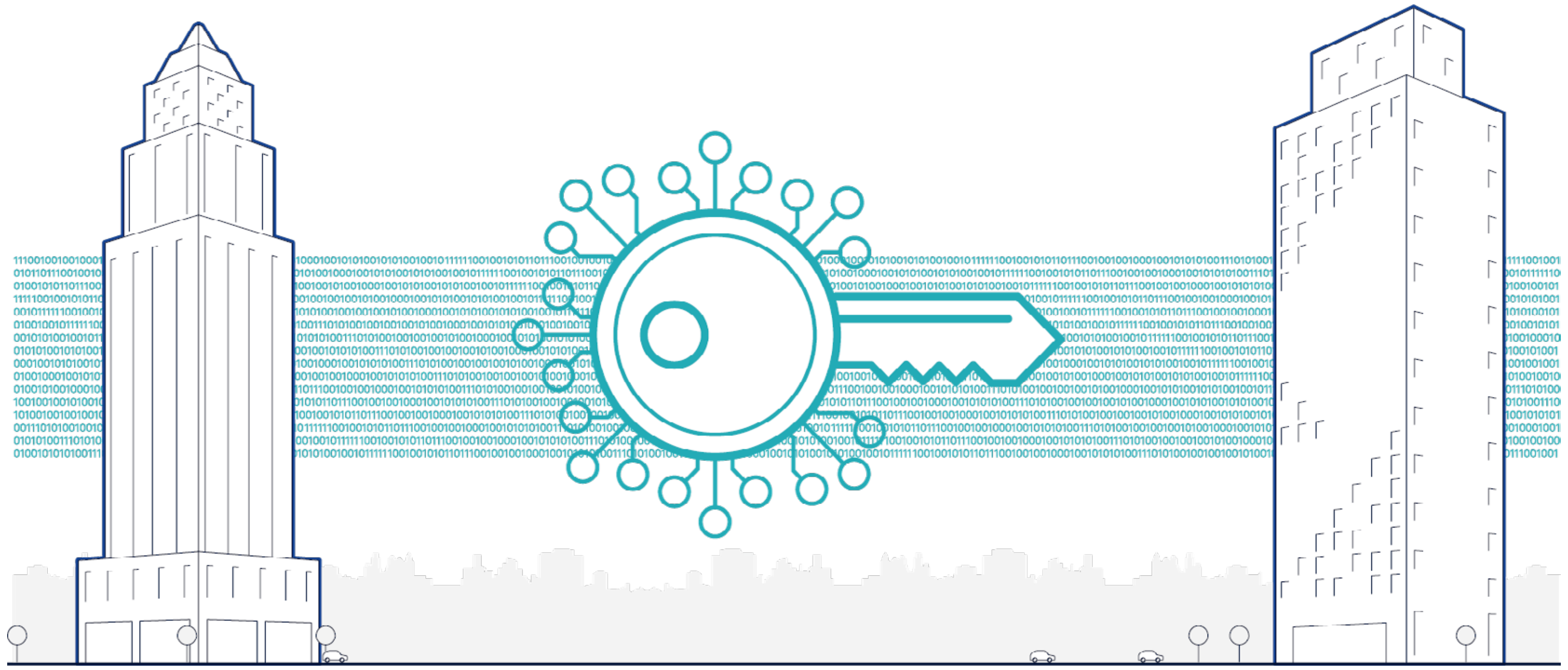
The emergence of quantum computing and quantum communications will have profound implications for security technologies and cyber-resilience. By applying principles of quantum physics, we are creating computers with unparalleled capabilities and communications channels with unbreakable encryption. But the same applies in reverse. Those same technologies can be used to compromise security measures once thought impenetrable.

While the underlying mechanisms of quantum physics in the context of quantum communications are well understood, there remain fundamental challenges to the practical implementations of quantum switches, routers and error-correction technologies when building computing infrastructure at scale. However, we must start preparing for a quantum-computing future now.

Today's asymmetric cryptographic algorithms will likely need to be replaced with quantum-safe concepts.

And in the case of sensitive data of long-term relevance such replacement needs to be tackled now so we can protect today's data stored on servers against future quantum-compute-based algorithms. Novel quantum algorithms such as Quantum Key Distribution may provide a new approach to secure 6G networks and protocols. Meanwhile, quantum safe cryptographic schemes such as lattice-based or code-based approaches are currently showing much promise.

> "Today's asymmetric cryptographic algorithms will likely need to be replaced with quantum-safe concepts"



Defending the factory floor

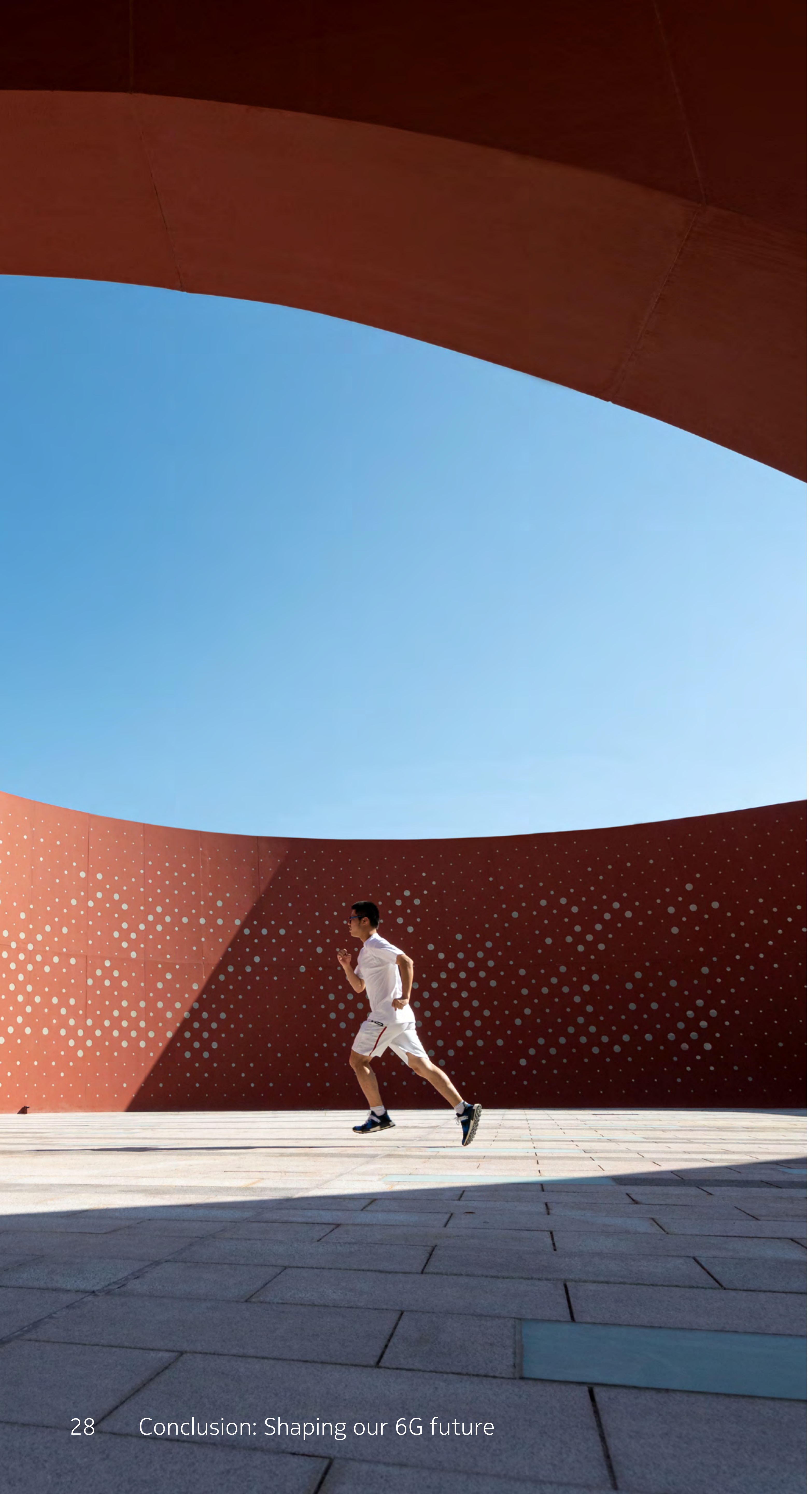
Campus and localized specialized networks will become the norm in the 6G era, and those networks will increasingly become targets of security attacks. Jamming a private network could bring a factory operation to screaming halt. Or worse, the high level of automation in future factories could lead to more sophisticated types of industrial sabotage. Rather than just shutting down a network, an attacker could attempt to take over the robots and machines connected to it, creating chaos on the factory floor, costing millions due to lost production time and even causing damage or injury to the people working on it.

6G era industrial security measures must be able to mitigate these attacks with technologies such as jamming detectors, directional null steering for uplink jamming mitigation and frequency hopping.

Security, privacy and trust are must-have technologies of the 6G era, but they are far from the only ones. Nokia Bell Labs is researching multiple technologies that we believe will define the 6G networks of the future.

Without security, privacy and trust, however, the 6G era would be moot. 6G will bring amazing new capabilities to the network and enable countless new applications that will help the world act together. But unless consumers, businesses and industries are comfortable that those networks and applications are secure, private and trustworthy, they will never embrace them.

> “6G will bring amazing new capabilities to the network and enable countless new applications that will help the world act together. But unless consumers, businesses and industries are comfortable that those networks and applications are secure, private and trustworthy, they will never embrace them”



Conclusion: Shaping our 6G future

By Peter Merz and Peter Vetter

This eBook represents an overview of our current thinking and efforts on the evolution of networks into the 2030s and beyond. As we have emphasized throughout the different chapters, 6G will build on existing technologies and systems, especially 5G, by improving performance and meeting the needs of new use cases — as would be expected. In somewhat of a departure, however, our 6G research is also focused explicitly on meeting important social values that have not traditionally been such an explicit part of the standards development process.

Evaluating 6G on its ability to meet key value indicators around sustainability, trustworthiness and digital inclusion is not merely a reflection of our current preoccupations. It is a recognition of the critical role networks are now playing in every aspect of life and the responsibility that this places on us as researchers, architects and designers.

In the 6G era, the digital, physical and human worlds will become far more integrated. Our goals must reflect this level of integration and inter-dependency. We can no longer afford to simply measure our progress based on narrowly defined technological criteria or efficiency measures. The network is already playing an outsized role in how we live, work, collaborate and take care of our planet. As billions more people get connected, urbanization intensifies, and we strive to manage the limitations on energy and materials, the role of networks and 6G will only deepen. It is essential that we keep the larger context in mind as we imagine the new network.

Moving beyond voice, video and data communications, future applications in the 6G era will benefit from distributed compute services, intelligence and analytics capabilities, as well as sensing, spatial and temporal services for the localization of people and objects within their environments and the synchronization of their actions. Use cases that will be of particular focus include telepresence, enablement of sustainability, trust in embedded networks, hyperconnected resilient network infrastructures, and massive twinning and automation using both robots and cobots. These new applications and services will be deployed on an agile, fully cloud-based infrastructure with X-as-a-Service capabilities to enable new business models in a multi-party value ecosystem.

Peter Merz
Head of Nokia Standards

Peter Vetter
President of Bell Labs Core Research

The road to 6G

While the first 6G networks are not expected to be commercially available before 2030, we are already laying their foundations through innovations in 5G-Advanced in 3GPP Releases 18 and 19, as well as other key stepping stones on the path towards 6G.

These stepping stones include distributed massive MIMO, an AI-native network fabric, new spectrum and radio architectures and the evolution of intent-based automation.

Distributed massive MIMO

The enormous demand that will result from the development of new, more collaborative user experiences will require greater uplink performance from networks, without sacrificing downlink performance. Distributed massive MIMO (DmMIMO) is a stepping stone for new extreme massive MIMO cell-less wireless network concepts using existing and new spectral bands in 6G.

Nokia Bell Labs has proven in simulations that DmMIMO can increase the 5G uplink capacity between 60% - 90% compared to similarly configured systems with a single panel. We are collaborating with AT&T on the validation of DmMIMO and testing the proof of concept in the AT&T labs.

AI-native network fabric

With 5G and 5G-Advanced, we expect AI and machine learning (ML) to be introduced in many parts of the network including layers, functions and domains such as the RAN and core. AI and ML show a unique ability to achieve better performance at lower complexity in operations such as the optimization of beam forming in the radio layer, scheduling at the cell site with self-optimizing networks, and enabling frictionless orchestration across the multiple networks and stakeholders.

We expect AI/ML to evolve from being an enhancement in 5G to a foundation technology in 6G. Recognizing this, we are taking a clean slate approach that does away with the complexity and lets AI/ML figure out how to best communicate between endpoints. There is collaborative work that we're undertaking with NTT and NTT DOCOMO towards a first-ever 6G proof-of-concept of an AI-native air interface.

Other stepping stones

On other fronts, Nokia is also actively pursuing spectrum allocation in new mid-bands from 7–15 GHz to meet the capacity needs of Extreme MIMO. We are exploring new radio architectures and antenna designs to create low-cost solutions in these bands. We are investigating new materials, such as radio-on-glass, that allow for low-cost realization of near-THz radio systems.

One of the main pillars of 6G will be a new cognitive, simplified network architecture. Cloud-based microservice networks with intent-based orchestration and automation are being developed for experimentation and demonstration.

In addition, Nokia is engaging with major industry peers, customers, academia and research institutions globally to form a common view and direction for 6G to maximize the added value. Our current key engagements span the US, Europe, China and Japan. Nokia plays an instrumental role in establishing Horizon Europe's Smart Network and Services (SNS) joint undertaking through our leadership of the SNS Task Force and chairmanship of the 6G IA board. As well as being a founding member of the Next G Alliance and NSF RINGS, we are leading Hexa-X, which is the EU's flagship research initiative on 6G.

Let's all work together to shape 6G!

Find out more about the possibilities of a 6G future here

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