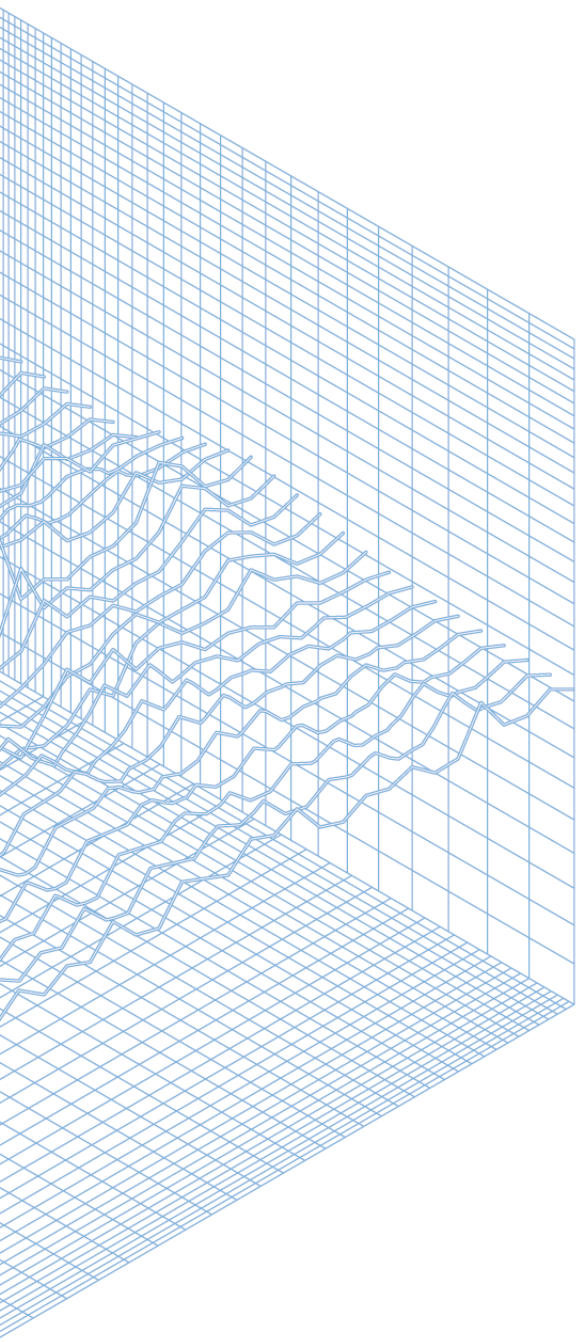
6G-RIC
Research and
Innovation Cluster

Toward 6G:
Key Directions and Research Questions

6G-RIC POSITION PAPER

Imprint



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Executive Summary

How to score a 100-fold capacity increase in an energy-efficient way? How to address privacy and security concerns specific to the convergence of communication and sensing? How to design semantic-aware communication protocols?

These are some of the key research questions to be answered in the transition toward 6G, according to the 6G-RIC Research and Innovation Cluster (6G-RIC) research roadmap.

At the heart of 6G-RIC are six Technical Innovation Areas (TIAs), which serve as technology drivers for 6G. Each TIA is associated with specific research challenges, whose resolution lies at the focus of the 6G-RIC research agenda. In this document, we formulate these challenges in the form of key research questions that should be answered within each of the six TIAs. Due to the interdisciplinary nature of the selected questions, 6G-RIC undertakes a holistic approach that simultaneously investigates hardware architectures, signal and protocol design, network computing aspects, as well as algorithmic and implementation complexity. In this context, energy efficiency and security play a leading role as horizontal aspects overarching all studied technologies.

6G-RIC Research and Innovation Cluster

The 6G Research and Innovation Cluster (6G-RIC) is dedicated to laying the scientific and technical foundations for the next generation of mobile communication networks (6G) across all technology levels, including radio access, core, and fiber-optic transport networks. Through cutting-edge research and international networking, 6G-RIC will help establish Germany and Europe as a leading global driver of sustainable 6G technologies.

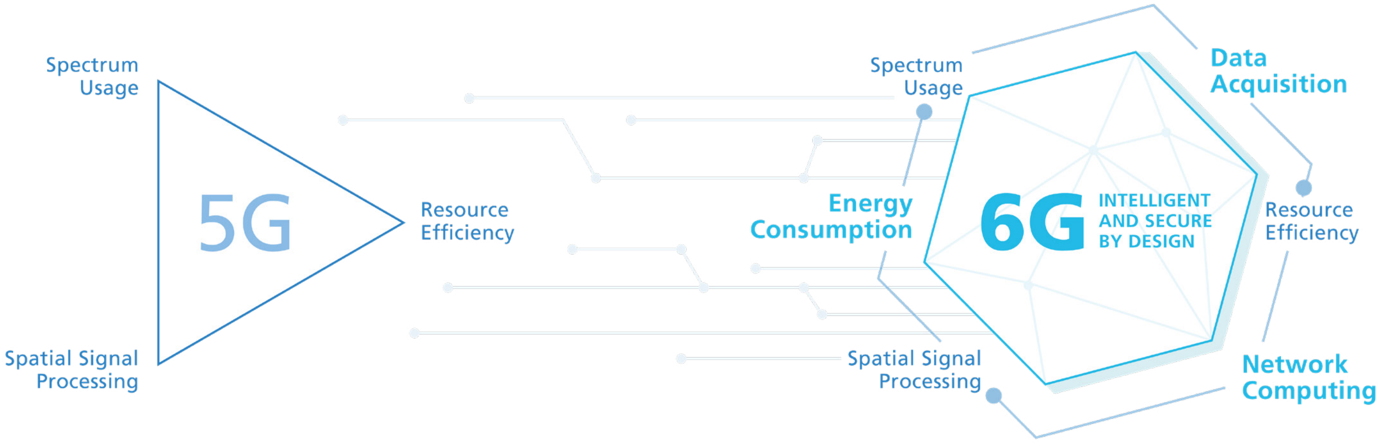
The focus of 6G-RIC is on the development of key 6G-technologies and their evaluation in the form of technology demonstrators in "living labs". Selected technology components will be brought together in overarching, end-to-end demonstrators and presented in the context of selected 6G use cases. The research work is flanked by the creation of an open infrastructure that will enable small/medium enterprises (SMEs) and start-ups to develop technology components and test them using state-of-the-art measurement technology in the lab and under real conditions.

Advanced communication technologies form the backbone of a modern and open society.

A secure, flexible, and open communication infrastructure forms the backbone of a modern and open society and is essential as the basis for successful digitization. Of particular importance are the recently introduced 5G technologies and their ongoing evolution toward the next generation of mobile communications (6G). The advent of 5G opened the door to new mobile applications in various vertical industries such as manufacturing, healthcare, and logistics. Therefore, major telecommunications companies are forecasting a massive increase in investment in mobile networks for vertical industries. It is not yet clear what 6G will encompass, but it is expected to have the performance, flexibility, and resilience needed to deliver highly specialized services and operate mission critical networks. 6G is also expected to enable entirely new applications such as telepresence and mixed realities and highly customized applications, e.g., in telemedicine. Some of the applications have very demanding requirements in terms of data rates (more than 100 Gbit/s), latencies (sub-milliseconds), and reliability. These in general conflicting requirements must be met simultaneously, a demand that is no longer feasible with 5G technologies. The data rates of 100 Gbit/s and more in real-world mobile networks can only be achieved using frequencies in the sub-THz range (up to 300 GHz). However, efficient and cost-effective sub-THz communication calls for innovative approaches to transceiver design and data processing in conjunction with new developments in microelectronics. Nevertheless, 6G is not just about extremely high data rates and low latency. 6G will bring about a paradigm shift in wireless communications by integrating sensing and highly accurate positioning capabilities with real-time analytics (network as a sensor). This will enable Connected Robotics and Autonomous Systems (CRAS) applications such as mobile robot swarms. All this requires the development of highly complex, heterogeneous, and distributed systems, consisting of communication and control units, real-time computing infrastructure, data storage, and sensors.

Technical Challenges and Requirements for 6G

One of the greatest challenges of the technological transformation associated with 6G is to reconcile the expected explosive growth in data traffic, the integration of sensing services, and the massive network densification with the demand for global sustainability and fairness. Considering long-term climate targets and the rapid spread of wireless communications, a far-



reaching reduction in energy consumption in future mobile networks is not only an advisable economical target, but also of particular social importance. Similarly, security will play a crucial role for social acceptance and averting economic damage. Security has become a basic requirement at all levels of system and network design. Current estimates are that quantum computers/hardware of sufficient capability will exist by the time 6G is deployed. It is therefore essential that the security of 6G networks is built from the outset on techniques that can withstand quantum hardware attacks.

There is no doubt that artificial intelligence (AI) will be one of the key technology drivers for 6G. Although AI undeniably has enormous potential, it does not come at zero cost. The gains achieved through AI must be put in relation to the corresponding effort and resources required. When it comes to energy consumption, local computation is inexpensive compared to (wireless) communication, which requires a large amount of energy to transmit a bit from one place to another. As a result, we need to take a holistic approach to the transition from 5G to 6G, viewing AI as an integral part of the overall system (integrated AI). Only in this way can data be collected, processed, transmitted, and used in the most (energy) efficient way possible within a network. In short, 6G must realize the convergence of information, communications, and sensor technologies.

The Transition to 6G

The transition from 5G to 6G includes the expansion of the design dimensions. In the design of 5G, the focus was on optimal use of the scarce frequency resource by means of spectrally efficient waveforms and coding and, above all, by exploiting the spatial dimension through multiple antenna systems. For 6G, it is expected that the additional resources “Computing” and “Data” can be used while minimizing the exploitation of the energy resources. The use of the sub-THz frequency range will in turn reduce the scarcity of the spectrum resource, which means that the focus will no longer be solely on multi antenna technologies with high spectral efficiency. The additional 6G resources “Computing” and “Data” will be tapped by the (artificial) intelligence integrated in the network. In addition to this “network intelligence,” the inherent “security by design” built into the communication network is at the focus of the 6G system concept for the reasons mentioned above.

6G-RIC Research Program

To address the technical challenges, the 6G Research and Innovation Cluster (6G-RIC) comprehends an ambitious and interdisciplinary research program. In addition to security and cost efficiency, energy efficiency is a key design criterion. This justifies a holistic solution approach based on new metrics to quantify energy consumption and encompassing all relevant hardware and software components including energy-efficient AI (“Green AI”) algorithms. Thus, energy efficiency will influence the development of transceiver components for upcoming sub-THz communications, as well as learning compact representations of artificial neural networks to reduce energy consumption, neuromorphic approaches for on-device/edge intelligence, and equalization in optical networks.

Technical Goals

6G-RIC addresses important challenges at multiple technology levels covering radio access network (RAN), transport network, and core network (CORE).

6G | kWh

Energy efficiency is a key design criterion for 6G. This calls for a holistic approach to energy consumption that encompasses all relevant hardware and software components in the network, including energy-efficient AI algorithms.

6G-RIC addresses important challenges at multiple technology levels covering radio access network (RAN), transport network, and core network (CORE).

1. At the hardware layer, 6G-RIC will explore new transmitter and receiver concepts and components that include novel solutions for direct and intermediate frequency (IF)-based sensing, digital down-conversion, and reconfigurable antennas. At the low physical layer (Low PHY), 6G-RIC will study advanced wideband beamforming concepts and techniques. This work will be complemented by research on intelligent reflective surfaces (IRSs) for radio environment adaptation. 6G-RIC will develop hardware-based solutions for sub-THz communications through this holistic approach, opening up these frequency ranges for mobile use.

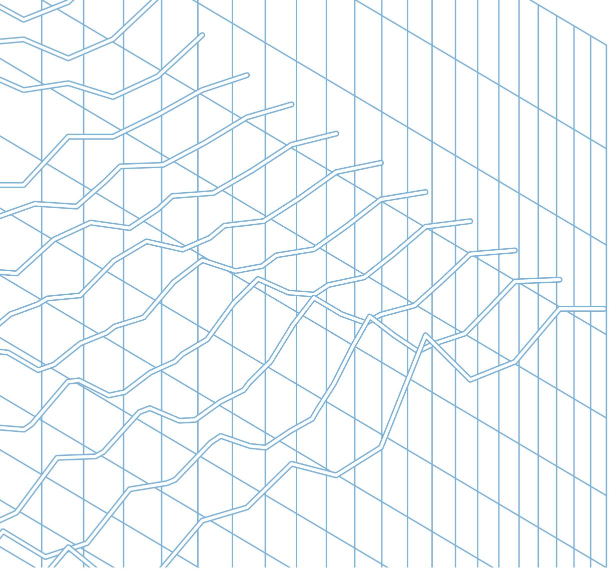
2. At the baseband processing level, 6G-RIC will build on current research on AI with the goal of efficiently implementing the RAN function in software in real-time on hardware virtualized platforms. This will be achieved using hybrid (data and model-based) AI/machine learning (ML) algorithms combined with massive parallelization. The goal: to increase efficiency and reduce memory requirements. A crucial element of the solution approach is the co-design of software and hardware, e.g., in the context of channel estimation under extended channel models and new sub-THz hardware architectures, or in the AI-based control of IRSs to influence the radio environment. Also considered are optical fronthaul solutions that support greater dynamics in network resource allocation.

3. New AI/ML approaches and dynamic pipelines for continuous adaptation of models require mechanisms for data acquisition. Among other things, "in-band network telemetry" provides the data basis for selective and on-demand acquisition of data from the network. In-band computing is used for filtering, aggregation and, if necessary, preprocessing of measurement data and training of models in operation.

4. The network layer with demand-driven and intelligent network management for optimized network operation of virtualized and programmable campus networks requires "human-in-the-loop" autonomous AI/ML-based control. An important aspect is also the development of end-to-end optimization frameworks for joint treatment of network resources (e.g., RAN, CORE, transport and cloud). Energy efficiency and "Green Design" principles (including "Green AI") must be inherently considered, also accounting for the effects coming from the disaggregation of network components.

5. One central aspect of 6G-RIC is the utilization of the paradigm of semantic communication, which deviates from the current communication paradigms by considering the context-dependent meaning and significance of transmitted information messages. In this respect, 6G-RIC adopts a goal-oriented viewpoint of communication systems where aspects of data acquisition, communication, and control are unified. In the context of emerging networked intelligent systems, the expectation is that the approach can yield significant savings in terms of both communication overhead and energy consumption.

6. Another central topic in 6G-RIC is a systematic analysis of security risks and threats. Based on a threat analysis, a security architecture will be designed that anchors the concept of security-by-design in 6G and increases resilience and platform security. Therefore, defense mechanisms against a wide range of attacks, such as eavesdropping, Distributed Denial of Service (DDoS), tampering with system components, or attacks on the control plane, will be considered from the very beginning of their development. To secure novel communication methods against attacks using quantum computers, which are likely to be available around 2030, new cryptographic primi-



tives such as low-latency quantum computer-resistant signature methods will be investigated in 6G-RIC. Another focus of the work will be on the integration of physical layer security (PLS) in the communication system design.

A horizontal activity in 6G-RIC is the development of channel models, which are indispensable for many of the research activities. Existing models need to be extended accordingly to provide a solid starting point for the development of sub-THz technologies and the integration of radio sensing services. Based on extensive measurement campaigns, realistic, site-specific channel models are to be developed, and radiation-based methods are to be integrated into quasi-stochastic models. Due to the excessive costs of measurement campaigns, the channel measurement data will be made available to the research community in an appropriate framework. The research community will thus be empowered both to participate in model improvement and to use the shared data directly for benchmarking and training of AI. In addition to making measured channel data available, there is also the possibility of making synthetic datasets sustainably discoverable for referencing purposes and publishing the associated source code.

Overarching Strategic Goals

In addition to the above technical goals, 6G-RIC pursues some overarching strategic goals. 6G-RIC aims to establish Germany and Europe as the world's leading drivers of sustainable 6G technologies through cutting-edge research and international networking. To this end, existing interdisciplinary competencies are to be bundled in 6G-RIC and cooperation between players in the field of 6G technologies, in particular sub-THz technologies, is to be intensified. Cooperation between research institutions in important future research topics such as security of communication technologies for the age of quantum computing, the unification of communication and radio sensing ("Joint Communication and Sensing"), massive connectivity, and network programmability are to be established and sustained. To this end, permanent networking structures are to be established at the national, European, and international levels.

A further objective of 6G-RIC is to create an open ecosystem for innovation and venture culture that can withstand the ever-increasing dynamics of the communications and smart services markets. The targeted modularization, virtualization and openness of future 6G technologies and infrastructures will for the first time open up opportunities for small and medium-sized enterprises to actively and disruptively participate in the world communications market. On the new basis of modularization and openness, there are numerous opportunities for German industry to enter the global market, especially in the area of campus networks (i.e., "private networks"), which are increasingly attracting attention worldwide as drivers of innovation. The development of intelligent communication technologies for future campus networks, which sometimes have to meet highly specialized industry-specific requirements, opens up a variety of new business models in the field of system design, optimization and integration of modular, open and secure radio technologies. It is expected that the number of campus networks will increase significantly in the next years. Against this background, 6G-RIC will help establish an ecosystem of SMEs, startups and large companies that will develop and benefit from 6G-related technologies. The role of 6G-RIC in this ecosystem is to provide knowledge transfer, as well as to contribute to the test- and development infrastructures.

6G must realize the convergence of information, communications, and sensor technologies.

Technical Innovation Areas

Technology Drivers for 6G

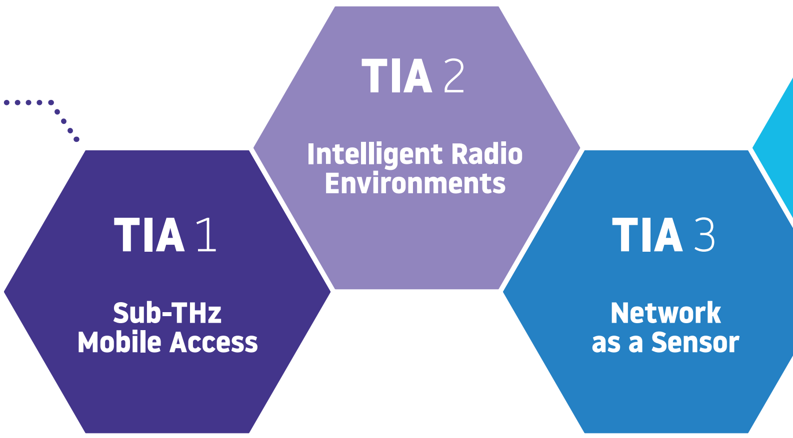
In the following, we summarize the 6G-RIC Technical Innovation Areas (TIAs), together with some of the (major) associated challenges. We dive more deeply into the technical aspects in the subsequent sections, where we formulate key/selected research questions associated with each of the TIAs separately and sketch the way forward in the scientific search for answers.

Sub-THz Mobile Access

Mobile access in the sub-THz band, also known as the upper millimiter wave band, is envisioned to be an essential component of future 6G networks. The main feature of the sub-THz band is the availability of sizable portions of underutilized spectrum, a necessary condition for realizing wideband mobile communication systems. The emerging bandwidth limitations of existing communication infrastructures should be addressed in such a way that not only a 100-fold capacity increase over the sub-6GHz band is robustly guaranteed, but also the energy and cost efficiency is significantly increased.

Intelligent Radio Environments

Contemporary wireless networks are designed based on the fundamental postulate that only the endpoints of the communication links, i.e., the transmitters and the receivers, are optimized to improve the network performance. Having the opportunity of customizing and controlling the environment may open up new opportunities for network optimization. IRS constitutes the key technology for customization of the radio environment. To make the concept practical, significant research efforts are required to provide realistic physical models and scalable algorithms for real-time IRS configuration and control. A holistic approach is thus preferred to overcome the existing shortcomings and fully exploit the potential of IRS-assisted wireless communication systems.

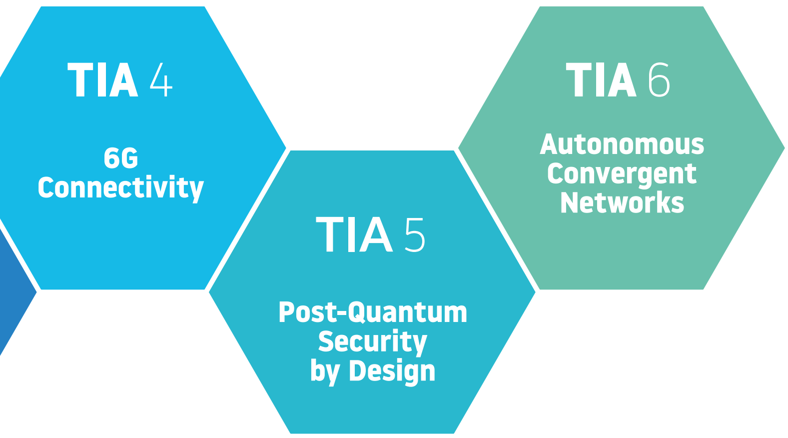


Network as a Sensor

An emerging trend toward 6G is the convergence (i.e., a joint and simultaneous offerning) of communication and sensing functionalities (including localization). These enable tracking and data processing, which are inherent features of applications such as extended autonomous systems. Convergence comes with multiple challenges, notably in the development of both hardware and software solutions that enable sharing of functionalities. An additional concern is related to privacy/security issues that might emerge as result of this convergence.

6G Connectivity

It is widely acknowledged that large-scale networks of devices communicating short messages to centralized or distributed/edge collectors will represent a key development area for future 6G networks. The use cases that next-generation Internet of Things (IoT)/Machine-Type Communication (MTC) systems should support are many and range from smart houses/cities (with sensors providing monitoring, for instance, of light/temperature conditions) to environmental sensing, intelligent automation in factories, health monitoring, and intelligent transportation systems. Each of the applications is characterized by specific requirements and side conditions, which should be taken into account in the system design.



Autonomous Convergent Networks

Convergence between communication and sensing, private networks, and AI/ML driven network- and user-centric services are among major application areas in 6G. Since these applications were not adequately supported by previous generations, it is clear that they require major innovations in networking, network management and orchestration, and network computing, among other areas. Hence, it is necessary to study the required innovations and to develop techniques addressing the problems related to these application areas.

Post-Quantum Security by Design

From both an economic and a societal point of view, it is essential to consider security and privacy as integral parts of network design from the outset. At the same time, the envisioned security approach must be flexible and sustainable enough to meet the challenges of anticipated technological developments. Therefore, the emerging threat of attacks by quantum computers and quantum hardware must be systematically investigated and defense mechanisms based on post-quantum cryptography and (quantum) physical layer security must be developed. Another focus lies on the defense against intrusions as well as on the detection of intrinsic malfunctions and functional conflicts in the network. This calls for a holistic security architecture for 6G networks that follows the paradigm of security-by-design.

TIA 1 Sub-THz Mobile Access

The exploitation of the large portions of available spectrum in the sub-THz band (90 GHz - 300 GHz) is one of the most promising directions for enhancing the capacity of current mobile access networks [1]. Due to the physical properties of sub-THz signals, the classical cellular paradigm based on deploying bulky base stations covering large areas will likely be replaced by the diffuse deployment of many small access points with low, highly optimized, and spatially targeted radiation. However, the design of cost- and energy-efficient sub-THz access networks is a formidable challenge that requires a complete mastery of the entire value chain of a wireless system. Among other things, the following main questions require significant investigation.

How to score a 100-fold capacity increase?

Traditionally, the capacity of wireless networks increases by means of cell densification [2], by using technologies offering high spectral efficiency such as massive MIMO [3], or by allocating more bandwidth [1]. Sub-THz networks are no exception, and they will rely on all the aforementioned ingredients, but giving particular weight to bandwidth. In contrast, due to spectrum scarcity, sub-6GHz networks must evolve by stretching the massive MIMO concept to its limits, especially in terms of spatial multiplexing gain. Following fundamental communication-theoretical guidelines, the following major difference appears when targeting a 100-fold capacity increase over current networks. While the sub-6GHz band is more suitable for splitting the capacity among a large number of relatively low-rate users, the sub-THz band supports much higher data rates to fewer users, hence it is the obligatory choice for the most rate-demanding 6G applications. Specifically, we expect sub-THz systems to achieve this ambitious goal by signaling over very large bandwidth, by simultaneously serving a moderate number of users on the same time-frequency resource, and by using relatively low per-user spectral efficiencies. Several questions remain open, for instance related to cell size and density, or, more generally, to network architecture and operation regimes, in particular in comparison with intermediate solutions in the lower millimeter wave band. A thorough system level analysis is of crucial importance to steer the development effort as early as possible in the right direction and is a primary objective of the 6G-RIC.

How to ensure connectivity under mobility?

Sub-THz waves are known to propagate for very short distances only, and to be easily blocked by walls, humans, and objects, hence possibly degrading the capacity gains enabled by large bandwidths. To guarantee reasonable coverage, highly directive beamforming antennas must be employed at both the transmitter and receiver ends. This poses considerable challenges on both the software and hardware side, as these antennas need to be electronically steerable and maintain alignment as the terminals move. However, these challenges may be mitigated by the exploitation of contextual information, which, in some form, is expected to be integrated in most 6G networks. Of great relevance here is the validation of the postulate that, at sub-THz frequencies, beamforming can be performed by means of quasi-optical arguments rooted on the so-called beam-space representation [4]. Furthermore, a promising option to counteract blockage effects is the implementation of novel multi-connectivity concepts going beyond the 4G and 5G control plane approaches [5]. To investigate the practical feasibility of the above ideas, many measurement campaigns and testbeds are planned within the 6G-RIC project.

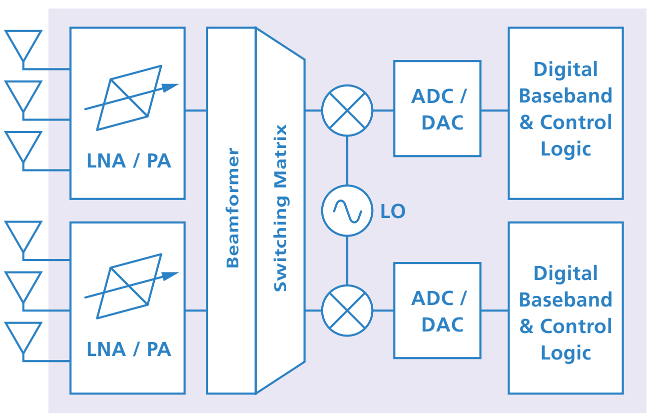
How to avoid excessive energy consumption?

A naïve design of software and hardware components of sub-THz networks leads to an unacceptably high energy consumption for both infrastructure and battery-powered devices, and, most importantly, in the context of the global climate targets [6]. The key issue is that improving the energy efficiency of each individual transceiver component in isolation will no longer be sufficient. This calls for a profound and multi-disciplinary rethinking of the entire system. A first important aspect considered by 6G-RIC is the hetero-integration of multiple semiconductor technologies, a problem that is subject of intensive worldwide research and covers integration at both the chip and package level. A second investigated aspect is the analog-digital design trade-off. On one hand, the co-design of modulation formats and digital signal processing algorithms inherently robust to nonlinearities may sensibly relax the hardware design constraints and leave room for energy savings. On the other hand, by moving some of the digital signal processing to the analog domain, the resulting losses in performance and flexibility may be outweighed by significant energy savings. In addition, the interplay with the network architecture will be considered. In particular, the per-area or per-user energy consumption needs benchmarking against current sub-6GHz solutions.

Which beamforming architecture?

The most prominent embodiment of the analog-digital design trade-off is the popular debate on beamforming architectures [7]. The 6G-RIC preliminary identified modular hybrid solutions composed by multiple independent phased arrays as the most promising solution from both an energy efficiency and integration point of view. However, additional work is required on the following aspects: (i) compromise between scanning range and quality of the phased array; (ii) comparison against more powerful yet more complex architectures involving analog amplitude control and true-time-delay lines; (iii) benchmarking against low-resolution digital beamforming architectures involving realistic impairments, e.g., on synchronization, channel estimation, and equalization; (iv) investigation of alternative analog beamforming technologies based, e.g., on quasi-optical solutions or IRSs.

a)



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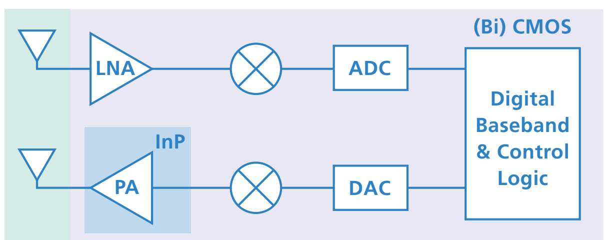

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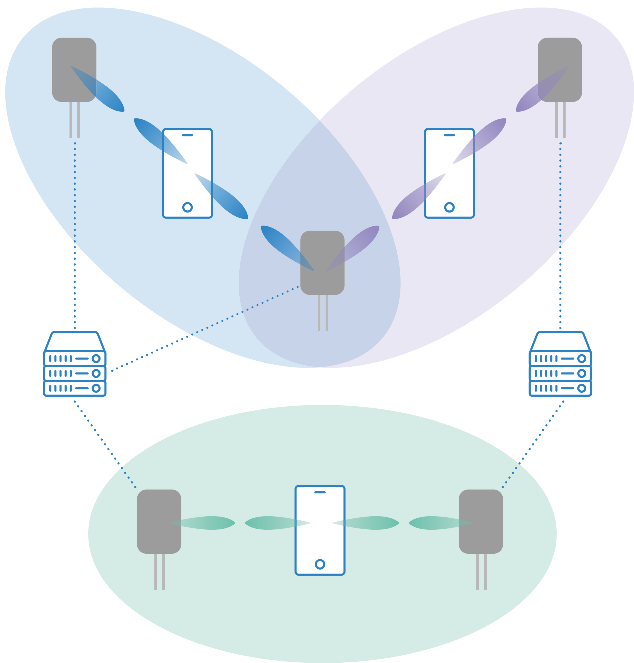


Energy Efficiency and Link Reliability as Driving Design Metrics
6G-RIC will explore several solutions for energy-efficient and reliable sub-THz mobile access networks, such as: a) modular and scalable hybrid beamforming designs; b) synergetic effects from hetero-integration concepts; c) advanced user-centric multi-connectivity architectures.

TIA 2 Intelligent Radio Environments

The introduction of IRSs challenges the conventional wisdom that the "channel is given" because it enables us to influence the effective channel without using conventional relays equipped with active elements. However, IRS-assisted wireless communication systems are still very much in their infancy, and some crucial questions remain largely unanswered, as elaborated in the following.

Are IRSs a disruptive technology or a new hype?

While IRS technology has some technical features that go beyond current technologies, to motivate the practical IRS development and the integration in communication systems, several questions have to be answered, in particular regarding: (i) the choice of the appropriate hardware technology, in terms of performance efficiency, cost, and complexity of design and manufacturing; (ii) the selection of convincing use cases, where IRS technology can excel and provide significant advantages over other competitive technologies; (iii) the aspect of modelling and integration in radio access, such that algorithms and protocols can be evaluated in a running system setting, and (iv) the development of scalable schemes for channel acquisition/estimation and algorithm design for real-time IRS control.

In the past, competitive technologies such as relays had been perceived as a promising solution to customize the propagation environment, but to date they are rarely used in practice. To find out whether IRSs can be successful in an area in which relays have failed so far (i.e., changing propagation characteristics), a promising direction is to study their application in the context of some selected use cases (see figure p.13), such as, e.g., (i) relaxation of the Line of Sight (LOS) requirement of Non Line of Sight (NLOS) links in highly directional communication systems [8], (ii) secure communications by providing link advantages over potential eavesdroppers in the context of physical-layer security [9], and (iii) rank increase of multiple-input multiple-output (MIMO) channels in order to provide multiplexing gains [10]. Several studies show that, from the perspective of spectral and energy efficiency, IRSs bring noticeable gains only with large surfaces with a large number of elements [11]. Therefore, in addtition to the IRS modelling, a major focus of the research in this context will be on the development of algorithmic solutions capable of performing CSI acquisition/estimation and real-time IRS control (IRS reconfiguration). In practice, this will require solving large-scale optimization problems that are typically discrete, nonlinear, time-varying, and NP-hard. Consequently, we cannot expect algorithms that are both optimal and fast, so novel heuristics that scale to large systems are required. An additional aspect that will be addressed is interoperability, i.e., when two or more operators provide services to users in the same region. In that case, the IRS deployed by one operator may unintentionally impair the performance of other operators. Mechanisms able to deal with situations of this type need to be developed.

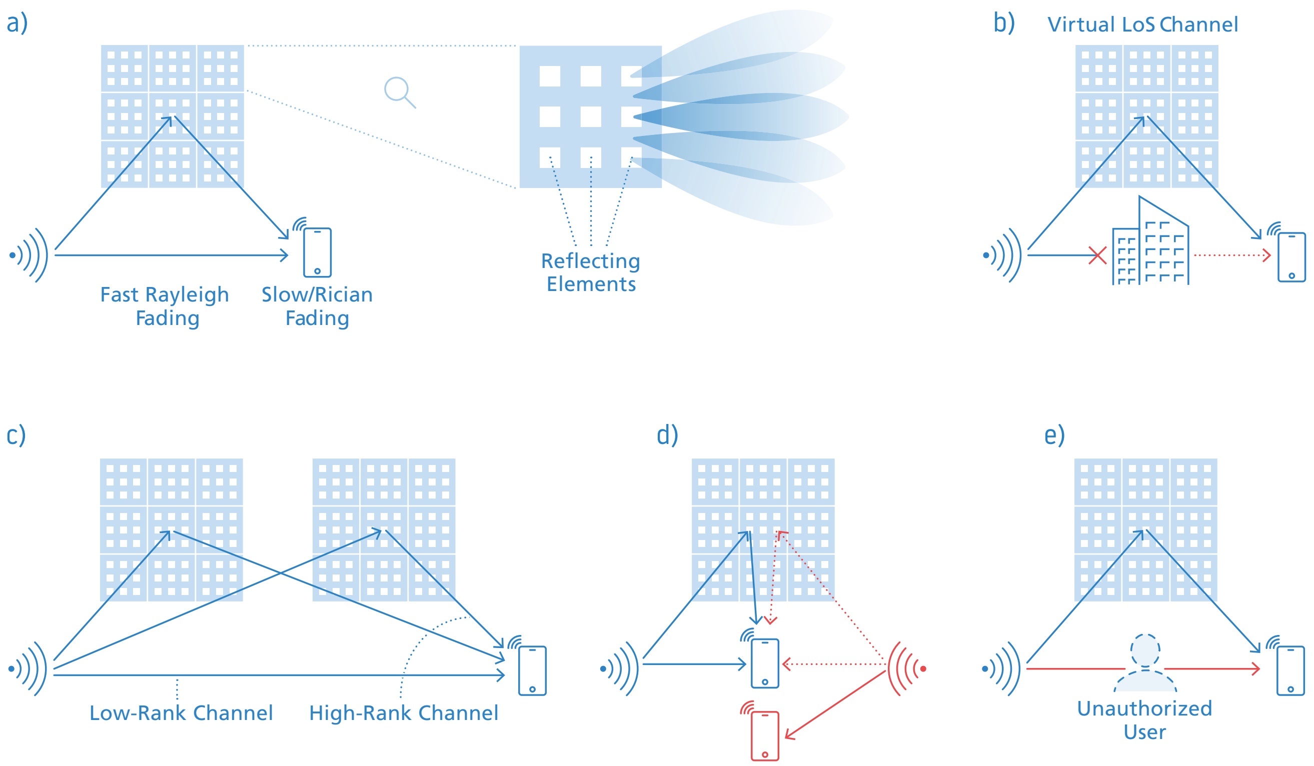
Are there mathematically tractable models able to capture the main features of IRSs?

Starting from the conventional wisdom that "all models are wrong, but some are useful" [39], we need "sufficiently" realistic models that capture the main features of IRSs, while still being mathematically tractable for a given design and evaluation goals. Depending on those goals, models with different tradeoffs between accuracy and complexity are required. Existing Independent Diffusive Scatterer-based (IDS) models [12] are overly simplified because, among other things, they do not consider imperfections in the construction of IRSs, the nonlinearities of transceivers, and antenna coupling effects. These impairments may put the actual performance of the communication system far from its theoretical performance, especially at high frequencies. As a result, new sophisticated models are required (e.g., [13]), but whether impairments of this type can be easily captured requires further investigation. One possibility for coping with the above impairments is to combine models based on physics with data-driven models in hybrid approaches. This produces two main benefits. First, compared to pure data-driven models, hybrid models may drastically decrease the amount of training data because inconsistencies with physical laws are promptly ruled out. Second, compared to physical models, hybrid approaches use data not only to capture hidden or unknown physical features that are hard to model, but also to deal with the vagaries of the wireless environment. To validate models with the above features, in 6G-RIC we propose not only to implement IRSs, but also to conduct measurement campaigns. These measurements will be used as the basis to develop IRS simulators, which are largely missing in the literature.

IRS in action: how to realize a hardware/ software co-design?

IRSs have a large potential to reduce the energy consumption and costs. This is particularly true for passive surfaces that do not entail active elements (and thus no RF (Radio Frequency) chains and amplifiers) or have only a few active elements. For such surfaces, the energy consumption is dominated by the hardware/software modules controlling the re-configurability of the surface. Considering potentially large surfaces, beyond the need for scalable algorithms, it remains to be demonstrated whether any algorithmic solution can enable energy-efficient real-time re-configurability, especially under mobility conditions. Since IRS requires a power source for re-configurability and wireless control channels, the control interface will likely have a considerable impact on the overall power consumption of the IRS, which could, in the worst case, even cancel out the expected advantages of IRSs in terms of energy-efficiency and costs. Therefore, in 6G-RIC, the focus will be on the design of algorithmic solutions that consider both hardware and software constraints, targeting practical implementations. Candidate techniques include the unfolding of iterative algorithms on neural networks (deep unfolded neural networks), which can be effectively implemented on dedicated graphics processing units (GPUs).

Another practical aspect that must be taken into account is related to the capacity of the feedback line, which is used to transmit configuration messages from the IRS controller to the panel. More specifically, practical lines have limited capacity, which imposes restrictions on the update rate and on the number of variables that can be considered by the algorithms. As one of the main competing technologies for IRS is the dense deployment of access points, the operation and deployment costs of IRSs should be low compared to those solutions.



IRS in Action: Selected Scenarios in which IRS Technology can be Competitive
A summary of attempts to address the questions of "where," "when," and "how" IRSs are useful. The main potential benefits are a) enhancing connectivity by modifying the statistics of channels, b) lowering the likelihood of a link outage by creating an alternative channel - so-called virtual LOS channel, c) increasing the rank of MIMO channels, d) suppressing interference, and e) increasing the secrecy rate in the context of physical layer security.

TIA 3 Network as a Sensor

Future wireless networks will have to support ubiquitous communication, together with highly accurate sensing (and localization) services. In light of these trends, it is of interest to study the different aspects associated with the convergence of communications and radio sensing, including waveform design, "channel charting"-based localization solutions, information fusion across multiple terminals, and processing of sensed information. An important observation is that the joint consideration of communication and radio sensing leads to new multidimensional optimization problems, where communication-related key performance indicators (KPIs) have to be balanced not only against each other, but also against sensing requirements such as classification and localization errors. In this context, the following research questions are of particular relevance.

Which use cases and applications will serve as catalysts for the convergence of sensing and communication?

Novel intelligent sensing and communication technologies are of high interest to leading industrial players, in particular in the context of intelligent/autonomous mobility and industrial automation. These applications are thus expected to serve as catalysts for the development of solutions that integrate communication and sensing capabilities. For example, the expected coexistence of radar sensing and communication in future connected vehicles calls for an approach that involves a joint design of hardware, waveforms, and signal processing, among other aspects. Similarly, in industrial scenarios, the application of joint communication and sensing enables agents to perceive the environment, which allows them to perform tasks that require a certain level of environmental understanding. In industrial automation, e.g., machines would benefit from being able to recognize or detect the objects in their proximity, thus assisting in the monitoring and safe operation of manufacturing lines.

What levels of convergence of communication and sensing do we expect? What will be the implications on hardware and system design?

Depending on the driving applications, the following levels of convergence of communication and sensing are foreseen [40].

Coexistence: Sensing and communication are not connected via 6G but sensing benefits from the hardware and software developments in the context of 6G. Examples include sensing systems benefiting from the development of sub-THz technology, IRSs and, in general, from R&D and manufacturing/testing capabilities of the 6G ecosystem.

Cooperation: (i) Sensing enabled by 6G connectivity, but where the sensing part is not co-designed with the 6G air interface, and (ii) communication enhanced by sensing, where various levels of contextual information (e.g., collected via sensing/localization) are utilized to enhance network performance (e.g., radio resource management, beam operation, interference management, and handover).

Integration: Sensing and communication partially or deeply integrated, where (i) tailor-made sensing signals are part of the 6G air interface design or sensing reuses the communications signals (partial integration), or (ii) signals for concurrent communication and sensing are jointly designed (deep integration). In both cases, sensing and communication use the same infrastructure and share hardware components.

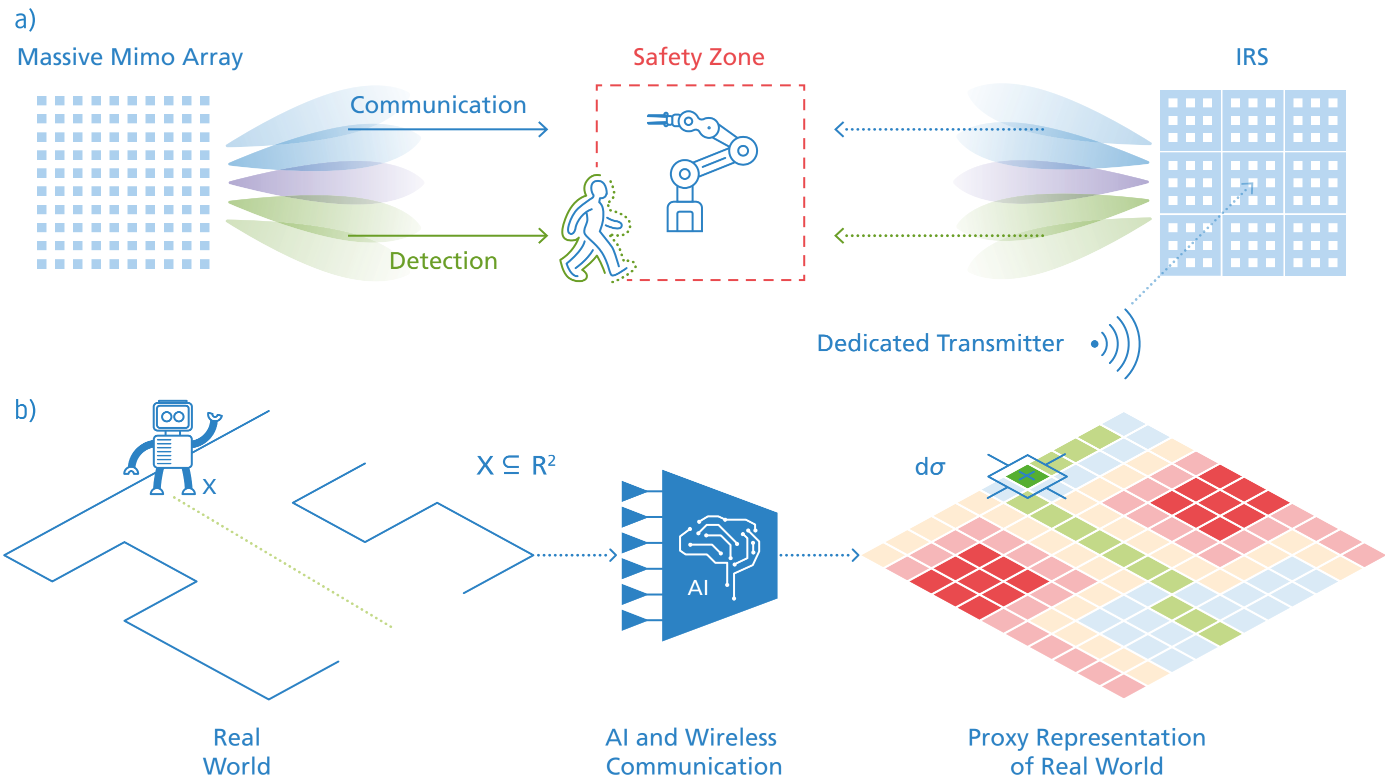
Depending on the level of integration, the standard KPIs associated with different applications should be mapped to requirements on signals/waveforms, hardware architectures, and deployments. In this context, one aspect studied in 6G-RIC will be the utilization of signal processing techniques in the time-delay-Doppler domain for sensing applications. This includes, among other things, the development of precoding and CSI feedback schemes (and corresponding signalling aspects) for communication and sensing. Applications include object detection and tracking, especially for mobility (industrial and automotive) scenarios, at both sub-6GHz and sub-THz frequencies.

How can contextual information (including infor mation obtained by sensing) be exploited to enhance network performance?

This aspect may be included as a part of a general framework that would allow a complete, low-dimensional representation of the radio environment to be learned in a process resembling channel charting [14]. The main objective is to learn low-dimensional embedding from a large amount of high-dimensional channel state information (CSI) of transmitters. Ideally, the embedding should locally preserve the original spatial geometry, i.e., transmitters that are nearby in real space will be placed nearby in the low-dimensional channel chart and vice versa. According to the approach taken in 6G-RIC, the resulting charts will be used to enhance network functionalities such as, e.g., radio resource management, beam management (mm Wave and sub-THz), cell association, and handover. An attractive property of these approaches is that the low-dimensional representation can be learned in an unsupervised fashion from CSI only and without assumptions on the physical channel. This important property enables geometry information about the transmitters to be extracted in a passive manner, paving the way for a broad range of novel applications.

Are there privacy/security concerns specific to the convergence of communication and sensing?

The convergence of sensing and communication may pose some unique challenges to both communication security and privacy. For example, in dual radar and communication systems, the inclusion of data in the probing signal, used to illuminate targets, makes it prone to eavesdropping from potentially malicious targets. Even if the data itself is protected with higher-layer encryption, the existence of a communication link can still be detected by a malicious agent, thus making it prone to cyberattacks [15]. In addition, the introduction of sensing capabilities and explicit localization of users/devices to improve communication network performance may come with privacy concerns. Faced with these challenges, 6G-RIC will assess the potential of certain approaches to provide secure, privacy-preserving solutions at the radio access level. From a privacy perspective, it is essential to collect only user-related data that is absolutely necessary for the operation of the network, thus potentially moving away from the explicit localization paradigm. In addition, appropriate privacy-enhancing technologies should be integrated, e.g., differential privacy. An example Is provided by the use of channel charting as a tool to enhance network functionalities. As channel charting relies on a pseudo-location (i.e., location in the low-dimensional chart) of the users (rather than on explicit localization), it potentially comes with a privacy protection feature, allowing localization-related services to be delivered without requiring the actual user location to be estimated.



Convergence of Communication and Sensing

Exemplary application of joint sensing and communication. a) Monitoring of safety zones in industrial scenarios. Potentially aided by technologies like beamforming and IRS, an existing industrial wireless link can be enriched with sensing capabilities to probe the air interface between transmitter and receiver and detect changes in the environment due to unauthorized access to a safety zone. b) Illustration of the channel charting concept. Contextual information regarding the wireless environment can be extracted in the form of a channel chart in an unsupervised or semi-supervised fashion. The resulting charts can be used to improve communication-related functionalities. By relying on a pseudo-location on a channel chart rather than on explicit localization in the environment, channel charting may potentially be seen as privacy-preserving.

TIA 4 6G Connectivity

While there have been significant research efforts to address different aspects of IoT/MTC, the vision of extreme IoT/MTC connectivity required for these diverse applications is yet to be realized. There is also a lack of consideration of E2E aspects as part of the design, i.e., the entire protocol stack from the physical layer to the application layer. In particular, it is necessary to study how current communication protocols can be adapted to incorporate aspects of semantic-aware communication on the different layers of the protocol stack. In light of these observations, the following research questions are of particular relevance.

What role will massive IoT/MTC systems play in 6G?

Massive IoT/MTC networks are expected to rapidly develop, soon surpassing other typologies of IoT/MTC. While most probably the vast majority of the wireless traffic will still be related to mobile/fixed broadband internet, the foreseen huge number of IoT/MTC terminals is posing a serious challenge to future system designers. In fact, while broadband internet traffic is largely predictable, and typically associated with devices with mild energy efficiency constraints, IoT/MTC often relies on battery-powered terminals that become active only sporadically. Therefore, the nodes are expected to be very simple (to reduce the energy consumption), possibly with very limited reception capabilities, and transmitting in an uncoordinated manner. These highlighted, specific features, together with the massive number of terminals, call for special attention in the design of future wireless networks.

What are the most promising techniques (e.g., wave forms, protocols) for massive IoT/MTC systems?

Most of the candidate solutions can be identified as modern random access (RA) protocols that can be well modelled by means of the information theoretic setting of unsourced multiple access (UMAC) [16]. Many of the most recent techniques (see, e.g., [18]) have been developed in the context of satellite-based systems and can be seen as enhanced variants of the classical ALOHA protocol [17]. Other techniques follow the approach of [16] by casting the problem from a compressive sensing viewpoint, engineering schemes that can detect messages from large codebooks (see, e.g., [19]). While the latter approach proved to be more energy efficient, it relies on strong synchronization assumptions that can be met only by terminals that can align their transmissions to an OFDMA-like frame structure. The earlier approach can also be used in asynchronous networks [20], at the cost of reduced efficiency. It appears clear that no silver bullet exists, i.e., no waveform among those cited would be capable, at the current state of knowledge, to address all scenarios of interest. Therefore, the research efforts in 6G-RIC will focus on a solution that can be flexibly adapted to the different conditions. In doing so, it cannot be ruled out that different waveforms will be ultimately employed to address the variety of scenarios.

What are the key enablers for designing low-power transceivers?

From a communication viewpoint, a fundamental figure of merit is the energy efficiency of the waveform/protocols used by the IoT/MTC system. In particular, schemes capable of operating close to the theoretical limits [16] (in terms of SNR for a given spectral efficiency) are highly desirable. An additional important aspect is the definition of the set of functionalities that a node should implement. For example, nodes that are equipped with transmit-only transceivers may prove to be more energy-efficient than nodes that are provided with transmitter and receiver capabilities, especially if the nodes spend a considerable amount of time in “listen” mode. To reduce the energy consumption, in this case, low-complexity receiver algorithms could be employed, as well as smart “wake-up” policies. To enable low-power solutions for on-device/edge intelligence, it will also be investigated how neuromorphic processing and spiking neural networks can be efficiently applied in the context of applications that involve event-based processing.

What flavor of semantic-based communications should be considered?

Several flavors of semantic-based communications can be identified. The simplest and most established approach deals with the setting of age of information (AoI) [21, 22] and the related generalizations [23, 24]. A second approach deals with joint source and channel coding (JSCC) enriched by a type-based multiple-access (TBMA) approach [25, 27]. A third approach promotes the concept of over-the-air (OTA) computation to enable the receiver to directly extract from the received signal, a function of the transmitted data that serves the ultimate goal of the underlying task/application. The above notions may be characterized as being goal- or task-oriented in the sense that of interest is the execution of a certain task with the performance being evaluated in terms of an appropriate semantic metric. An even more disruptive approach followed in 6G-RIC, though not strictly related to the massive IoT/MTC setting, deals with the problem of communicating generative models. The underlying principle is based on the fact that, sometimes, the object of the communication may not be a specific instance (e.g., "the picture of a cat") but rather a concept (e.g., "a cat"). In the context of the different perspectives, the information-theoretic foundation may be provided by the "information bottleneck" principle, where the aim is to extract and communicate only the necessary information relevant for the execution of a specific task. While all different perspectives are relevant, they come with different implications on the wireless network design. A fundamental understanding of these implications will thus be crucial for the wider adoption of semantic-aware communication in future 6G networks.

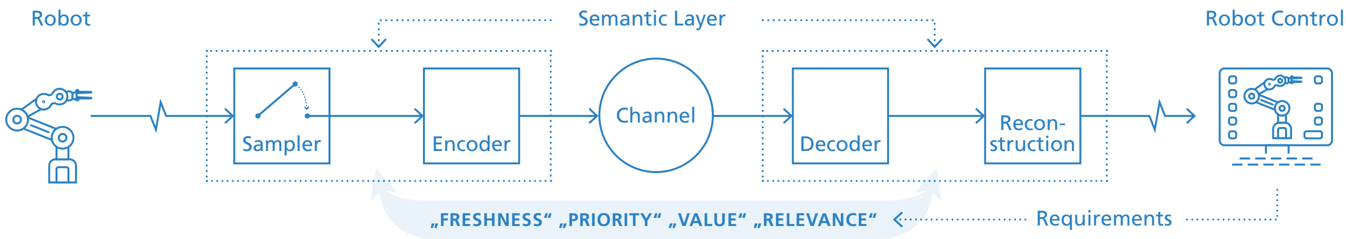
How could the semantic-based techniques be integrated in standards?

In principle, some flavors of semantic-based communication may be implemented directly at application layer: this is the case, for instance, with AoI-based designs. While this observation paves the way for the adoption of AoI-based techniques in existing standards (e.g., 3GPP), one should consider that to fully leverage the gains promised by information-freshness-driven designs, the underlying multiple-access channel (MAC) protocol should provide enough flexibility. Moreover, the possibility of standardizing methods to program the nodes' behaviors (e.g., through specific application programming interfaces (APIs)) would simplify the deployment of AoI-based massive IoT/MTC networks. Other techniques (TBMA and OTA computation) may require more substantial modifications, which may additionally include the physical layer. In all the mentioned settings, a fundamental aspect addressed in 6G-RIC deals with the impact, from a protocol stack viewpoint, of the techniques on the wireless network design.

How encryption should be performed, given the low computational capabilities of IoT nodes?

On the assumption of using public key cryptosystems (PKCs), IoT systems must be developed under a number of constraints: (i) encryption and decryption should be fast and easy to implement (in hardware), (ii) cipher text sizes have to be small to reduce the memory requirements, (iii) public keys must have a reasonable length and can be transmitted by low-energy devices or over bandwidth-limited channels. Code-based cryptography is in general significantly more efficient in terms of encryption and decryption complexity compared to classical public key encryption mechanisms (see, e.g., [28]), and hence (when designing schemes with moderate-small public keys) may represent a viable approach to the problem. Additionally, the use of physical layer security schemes (in synergy with lightweight crypto-systems) may further improve the security vs. complexity trade-off. An additional concept that is addressed in 6G-RIC is that of homomorphic encryption: Here, the idea is to encrypt messages at the IoT end, transmit them, and enable the recipient to compute some (aggregate) function of the incoming cipher text, which can then be deciphered. This approach might be of interest for applications in which (i) sensitive data is transmitted and (ii) we are interested in deriving only aggregated information about the messages sent by several IoT nodes (for example, in health monitoring applications, we may be interested only in statistics associated with certain behaviors).

a)



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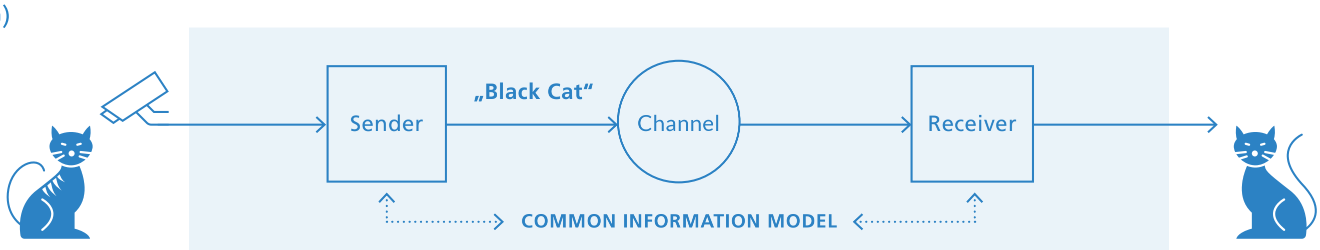


"Flavors" of Semantic Communication
Goal-oriented communication: a) a semantic-aware architecture for robotic control that considers a unification of the processes of information generation, communication, and usage, resulting in a reduction in communication overhead and energy consumption. Communication of generative models: b) the underlying principle is that the object of communication may be a concept rather than a specific instance. This aspect is closely related to the concept of the "information bottleneck", where the aim is to extract and communicate only the necessary information relevant for the execution of a specific task (i.e., goal).

TIA 5 Post-Quantum Security by Design

Previous generations of mobile networks viewed security as a feature added to an already fully developed network. In addition, many necessary security measures were only recommended, not prescribed, in the standardization, which led to a disadvantageous perception in society and insufficient security level. These shortcomings will be addressed in 6G-RIC through the development of a security by design concept. In the context of Open-RAN featuring disaggregation, openness, and interoperability, security must be considered from a holistic perspective, starting with network design. The new security architecture should be designed to deliver low-latency, resource-efficient, low-complexity, and application-aware solutions, while at the same time being powerful and flexible enough to cope with the risks and threats posed by future technological developments like practical realizations of quantum computer and advances in quantum communication technologies.

How to achieve a secure and open network architecture?

Security by design [29] describes the guiding principle according to which security considerations in early stages of system design lead to more efficient and resilient results than retrofitting the finished system with security mechanisms. In the context of Open-RAN and 6G, this means that starting from a system-wide examination of risks posed by open interfaces, roles and tasks of the stakeholders, as well as envisaged new functions in the network, an early inclusion of security considerations and a development of clear security concepts during the design of the network must take place. Among the most important measures to achieve a high level of security are mandatory encryption and access control as well as integration of security measures to defend against malicious cloud providers. In addition, the basic functionality of communication protocols and procedures must include privacy-preserving measures.

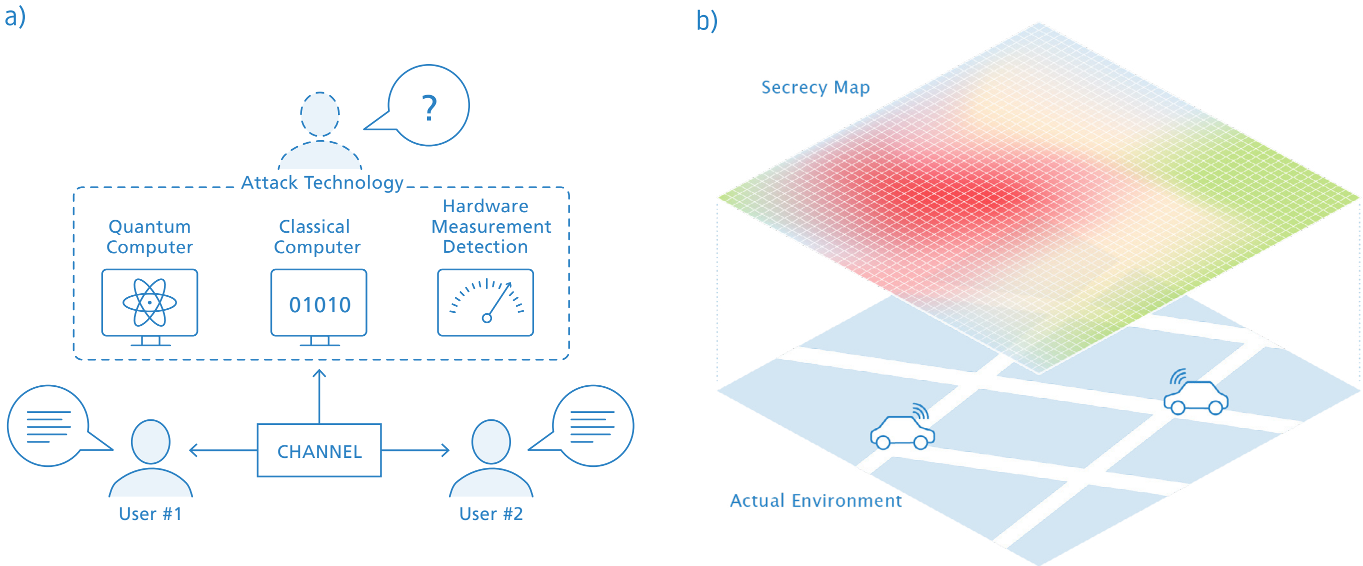
Due to their open and modular structure, Open-RAN networks may be vulnerable to intrusions and denial-of-service (DoS) attacks. Therefore, 6G-RIC will integrate efficient machine learning-based methods to detect this type of attacks. On the other hand, it is known that those methods themselves are prone to an attack technique referred to as adversarial machine learning so that a deeper understanding of the resulting threats and the development of intrusion-detection methods that are robust against adversarial machine learning are necessary.

How to develop cross-layer harmonized security concepts ready for the era of quantum computers?

Methods for securing Open-RAN networks should, as far as possible, affect all layers of the network and complement each other in functional terms. In addition to identifying and developing appropriate cryptographic resource-efficient protocols for encryption, authentication, and signatures, physical layer security will play a critical role. According to our viewpoint, one of the main enablers for integration of physical layer security are "secrecy maps" [30] which can be seen as a generalization of the concept of radio maps that take into account confidentiality in the physical layer. This way, the radio environment is quantitatively characterized in terms of (statistical) security level guarantees based on the semantic security measure in dependence on the positions of legitimate communication parties and the (unknown) position of a potential eavesdropper. Based on this characterization of the wireless environment, networks units such as base stations and IRSs can be employed in such a way that a fraction of their resources are used for communication among legitimate entities, while the remaining resources are used to deteriorate wireless links in a region that is particularly attractive for the potential eavesdropper. In this context, secrecy maps can be seen as an enabler and guide for an adaptive, proactive, and intelligent security management framework for wireless networks. An important question addressed in 6G-RIC is how to achieve synergy with cryptographic protocols at higher layers and what the impact on the security vs. complexity trade-off of such harmonized protocols is. Moreover, the rapid development of quantum computers and their potential ability to break some of the classical public key procedures, as well as the dynamic development of detection and measurement methods for quantum technologies that can be used for quantum side channel attacks, opens new attack surfaces that must be taken into account so that future-proof security can be guaranteed. Therefore, 6G-RIC focuses on the integration of the post-quantum cryptography methods currently available and, in the long term, quantum physical layer security.

Security as a service?

Due to the various application scenarios ranging from environmental monitoring and industrial control to telemedicine and vehicular communications, IoT is expected to support diversified services, possibly having entirely different requirements on quality of service (QoS) and security. For example, online payment requires a much higher security level than web browsing services. It can be expected that this servitization of information security would present security as a new type of service (e.g., like voice and data). For example, users can "buy" the security level based on their requirements and the cost, making information security a profit point for operators, as noted in [32]. As the concept has implications on resource allocation and link adaptation, in 6G-RIC we envisage the development of novel communication protocols as extensions of the concept of link adaptation to incorporate security. It is even conceivable that different levels of security could be of interest to different applications. Depending on the requirements on security and assumptions about the capability of attackers, one could provide custom tailored security levels rooted in different security methodologies: starting from state-of-the art cryptography for "standard" applications, and then including post-quantum security [31] for sensitive data that has to be protected over a longer period of time under the assumption that the attacker has/will have access to a quantum computer to run quantum algorithms that can break public key schemes. Alternatively, if the data is to be protected from side channel attacks via quantum hardware (like quantum detectors and receivers for quantum optical communication systems), it is conceivable to use quantum physical layer security as a basis for this task.



Integration of Physical Layer Security in the Communication System Design
Based on technological capabilities of the attackers, methodically different defense mechanisms are necessary: a) State-of-the-art cryptography offers suitable security solutions for attacks based on algorithms that run on classical computers; post-quantum cryptography and physical layer security both offer long-term security of data that should be protected against attacks by adversaries equipped with quantum computers [26]; side channel attacks based on detection and measurement with quantum hardware can be defended against with quantum physical layer security. b) Secrecy maps can be generated to characterize the wireless environment in terms of (statistical) security level guarantees. With respect to a predefined security metric (e.g., semantic security), they can be seen as an enabler for an intelligent security management framework for wireless networks.

TIA 6 Autonomous Convergent Networks

With the myriad of new communication technologies, vertical applications, and the emergence of private networks, 6G networks will require major innovations in networking, network management, and data handling. Furthermore, they will require extensive automation to reduce the overall overhead in network management, especially towards automatic updates and automatic configurations. In the following, we look at some major considerations for 6G networks in light of network convergence and emerging networking technologies.

What will be the impact of emerging 6G technologies on the network management and operation?

The emergence of sub-THz communication and the introduction of IRSs, together with the convergence of sensing and communication, will affect network architectures, network planning, management and operation. In the context of sub-THz communication, the narrow-beam operation comes at the expense of more advanced mobility management and handover strategies. In addition, the possibility to form multiple beams and provide multiconnectivity will require novel MAC and resource management mechanisms. In addition, the integration of IRSs will also have implications on resource allocation, user-IRS association, and IRS configuration and control. These issues are particularly challenging when considering large-scale IRS-assisted transmission scenarios where multiple BSs serve multiple users with the aid of multiple IRSs. At the level of network management, a joint consideration of communication and sensing leads to the definition of complex multidimensional optimization problems, where the KPIs of the communication and the sensing part have to be balanced against each other. In this context, 6G-RIC will address the implications on the system design, including: (i) definition of sensing-related services classes; (ii) definition of KPIs related to the new functionalities, for example related to the integration of contextual information; (iii) development of new MAC and radio resource management protocols to meet the needs of different sensing and communication services; and (iv) extension of the network slicing concept to support sensing functionalities.

Which major innovations in networking technologies are required to enable network convergence and vertical applications in 6G?

A major requirement on networking technologies in 6G is to extend wireless performance metrics (such as data rate, reliability, latency, energy efficiency, etc.) to new and vertical wireless applications, such as virtual reality industrial applications and mission critical services. However, these applications place requirements that are more stringent than the current 5G networks, and therefore innovations in networking technologies are necessary. For example, in the context of campus networks [35], a major goal is their embedding into public telecom infrastructure via network slicing and software-defined networking with virtualization, which promise fast resource/infrastructure provisioning and reliability in network reconfiguration, and fast rerouting. The convergence of sensing and communication, but also of networking and computing, will further require innovations in network telemetry [36] and intent-based networking [33]. Moreover, the stringent requirements on reliability, high data rate, and latency also require innovations in optical transport networks [37].

What impact would semantic communication have on network architectures?

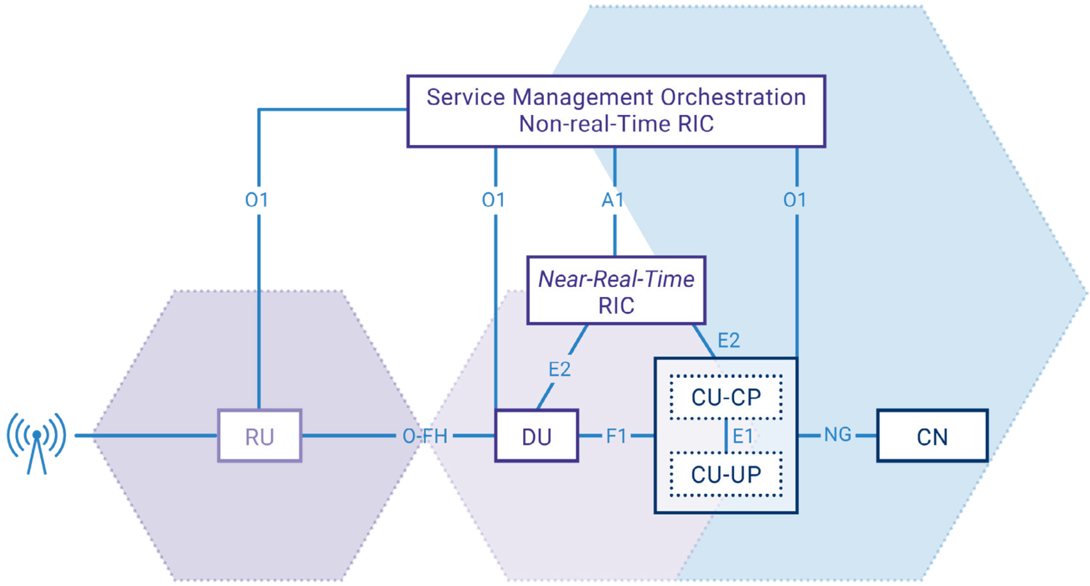
The incorporation of the semantics of information in networked systems [34] may represent a departure from the established way of designing and assessing communication networks. In a somewhat broader context, the semantics of information may be understood as “the provisioning of the right and significant piece of information to the right point of computation (or actuation) at the right point in time”. In 6G-RIC, the focus will be on the investigation of how semantic communication can be integrated in communication protocols. The integration might require new architectures and redesign of the process of information generation, transmission and usage, including (i) explicit enabling of semantic-aware networking, computing and communications to optimize the E2E performance with respect to semantics-related metrics such as AoI and extensions therein, and (ii) redesign of communication protocols to support functionalities such as, e.g., semantic-aware placement of network functions and the related flow control mechanisms.

Which type of computation and intelligence units shall an autonomous network include? How should such units be implemented?

Given the complexity, scale and distributed nature of the network infrastructure and management, centralized network optimization becomes impractical. To address this challenge, a few tightly coupled paradigms are emerging, including edge and cloud computing, AI/ML based networking and management (including intent-based networking) and convergence of heterogeneous computing and communications technologies with networking. New network functions can assist not only in managing the network optimally but also in addressing the users' demands. In the former case, using AI and ML methods on the available data (batch or online) returns the optimal network parameters, whereas, in the latter, the users can demand online computational services. To achieve the potential performance gains, suitable selection and placement of such functions is required, which depends on several factors, such as network topology, recurring mobility patterns, and similar.

Which advances in optical networking will be considered for 6G?

The optical X-haul network will play essential role in the future deployments of 6G. Due to the expected increase in the data rates, together with the stringent low-latency requirements for some applications, the optical transport will have to support greater dynamics in network resource allocation [38]. The potential solutions include bringing coherent optics towards access, i.e., solutions such as multi-carrier systems, adopting Wavelength Division Multiplexing (WDM) for access network (passive, active, or semi-active WDM), such that the cost can be justified, and finally different flavors of Passive Optical Networks (PON). In the domain of optical signal processing, neuromorphic computing is considered in 6G-RIC due to the energy-efficiency and low-latency. This concept can be employed for nonlinear optical signal equalization that will eventually enable the transmission of signals at speeds beyond the physical limits of electronic-domain approaches. One of the challenges for photonic neuromorphic computing that is investigated in 6G-RIC is the realization of optical-domain activation functions. The implementation of the overall architecture on a photonic integrated circuit will be a step towards an energy- and a cost-effective solution that will complement optical networks in the framework of 6G. The convergence of optical and sub-THz control and management planes will further enable innovation in 6G architecture, signaling protocols, and services.



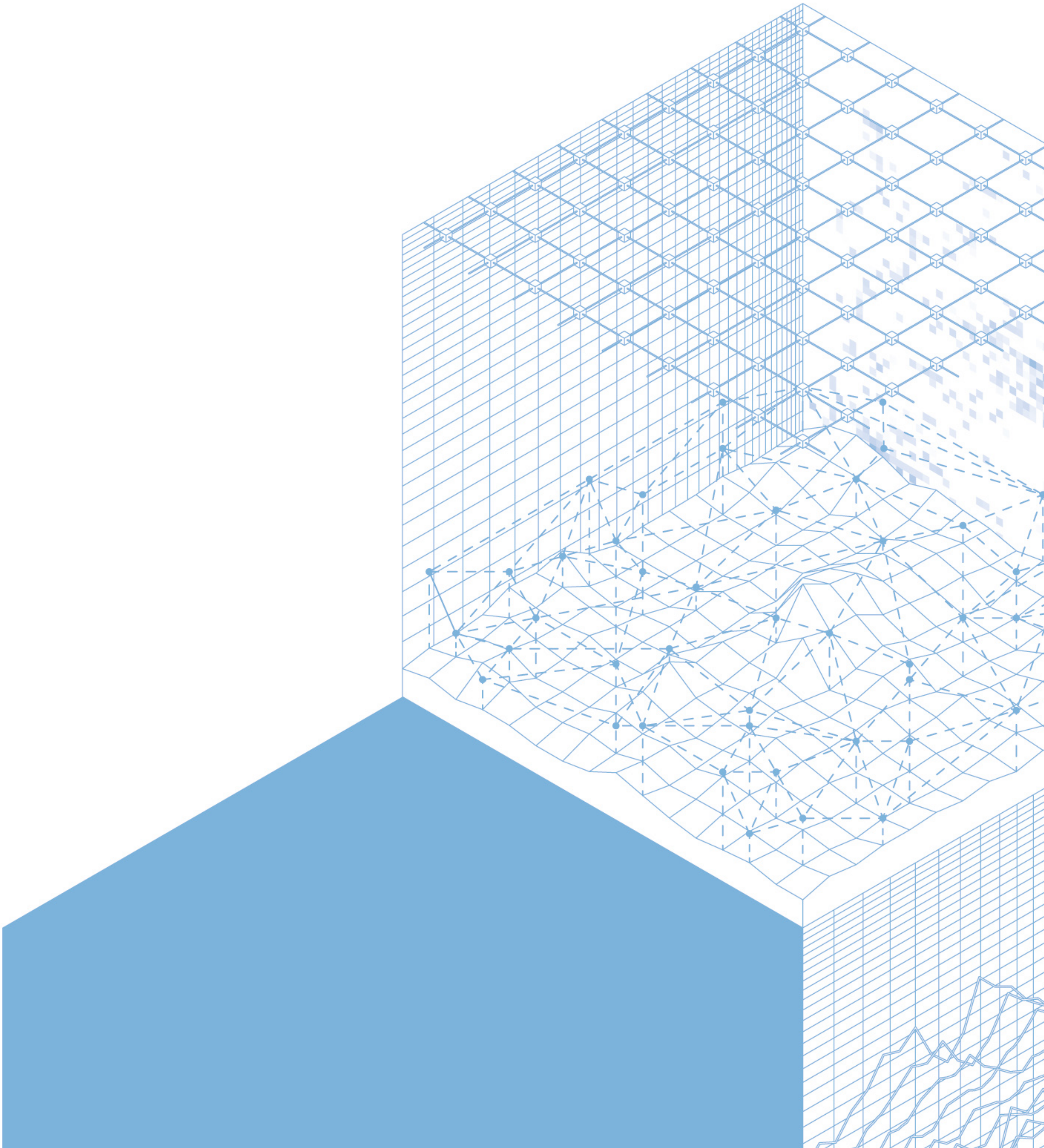
Convergence of Networking, Communications and Computing through Virtualization and Cloudification
An exemplary schematic representation of an OPEN RAN architecture, comprising of entities such as Radio Units (RU), Distributed Units (DU), Central Units (CU) and Radio Intelligent Controllers (RIC) (near-real-time and non-real-time), connected through open interfaces and protocols. Whereas the virtualization and softwarization of the CU is relatively simple, the same cannot be stated for the DU, which provides the real-time functions of the lower layers, which makes it challenging. In this context, the suitable selection and placement of RAN functionalities in new network architectures plays an important role.

Outlook

This document summarized the initial viewpoints and outcomes of the 6G-RIC research program. On a technical level, we identified a non-exhaustive yet representative list of key technical questions to be addressed within each of the six Technical Innovation Areas (TIAs). Several technology enablers and preliminary solution concepts were presented, together with their individual associated challenges, but also in light of their integration into a complex, secure, and energy-efficient 6G ecosystem.

Altogether, the selected questions motivate and define a research agenda that has at its center a holistic and multidisciplinary approach to tackle the horizontal aspects such as energy consumption, data acquisition, network computing and security. Future 6G-RIC investigations will strengthen the promising cross-topic connections identified within each TIA. Furthermore, additional promising research directions will be opened by deepening the connections across different TIAs, an aspect that is not covered in detail by the present document. The final aim of the research agenda is to provide concrete recommendations for the overall 6G system design, including hardware architectures, algorithms and protocol design.

In a more general context, by addressing these research questions, 6G-RIC will aim to influence the international developments of the sixth and subsequent generations of mobile communications and to anchor long-term strategies through early commitment and broad networking of interdisciplinary competencies.



Bibliography

[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, "Wireless Communications and Applications above 100 GHz: Opportunities and Challenges for 6G and Beyond," *IEEE Access*, vol. 7, pp. 78729–78757, 2019.

[2] N. Bhushan, J. Li, D. Malladi, R. Gilmore, D. Brenner, A. Damnjanovic, R. T. Sukhavasi, C. Patel, and S. Geirhofer, "Network Densification: The Dominant Theme for Wireless Evolution into 5G," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 82–89, 2014.

[3] T. L. Marzetta, E. G. Larsson, H. Yang, and H. Q. Ngo, *Fundamentals of Massive MIMO.* Cambridge University Press, 2016.

[4] J. Brady, N. Behdad, and A. M. Sayeed, "Beamspace MIMO for Millimeter-Wave Communications: System Architecture Modeling, Analysis, and Measurements," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 7, pp. 3814–3827, 2013.

[5] M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, "An Efficient Uplink Multiconnectivity Scheme for 5G Millimeter-Wave Control Plane Applications," *IEEE Transactions on Wireless Communications*, vol. 17, no. 10, pp. 6806–6821, 2018.

[6] P. Skrimponis, S. Dutta, M. Mezzavilla, S. Rangan, S. H. Mirfarshbafan, C. Studer, J. Buckwalter, and M. Rodwell, "Power Consumption Analysis for Mobile mmWave and Sub-THz Receivers," in *2020 2nd 6G Wireless Summit (6G SUMMIT)*, 2020, pp. 1–5.

[7] H. Yan, S. Ramesh, T. Gallagher, C. Ling, and D. Cabric, "Performance, Power, and Area Design Trade-Offs in Millimeter-Wave Transmitter Beamforming Architectures," *IEEE Circuits and Systems Magazine,* vol. 19, no. 2, pp. 33–58, 2019.

[8] C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "A New Wireless Communication Paradigm through Software-Controlled Metasurfaces," *IEEE Communications Magazine*, vol. 56, pp. 162–169, Sep. 2018.

[9] J. Chen, Y. Liang, Y. Pei, and H. Guo, "Intelligent Reflecting Surface: A Programmable Wireless Environment for Physical Layer Security," *IEEE Access*, vol. 7, pp. 82 599–82 612, 2019.

[10] Ö. Özdogan, E. Björnson, and E. Larsson, "Using Intelligent Reflecting Surfaces for Rank Improvement in MIMO Communications," Proc. *IEEE Intern. Conf. Acoustics, Speech, and Signal Processing (ICASSP)*, pp. 1–5, 2020.

[11] E. Björnson and L. Sanguinetti, "Demystifying the Power Scaling Law of Intelligent Reflecting Surfaces and Metasurfaces," *IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP)*, pp. 549–553, 2019.

[12] Q. Wu and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Network," *IEEE Communications Magazine*, vol. 58, pp. 106– 112, Jan. 2020.

[13] M. Najafi, V. Jamali, R. Schober, and H. V. Poor, "Physics-Based Modeling and Scalable Optimization of Large Intelligent Reflecting Surfaces," *IEEE Transactions on Communications*, vol. 69, no. 4, pp. 2673–2691, 2021.

[14] C. Studer, S. Medjkouh, E. Gonulta¸s, T. Goldstein, and O. Tirkkonen, "Channel Charting: Locating Users Within the Radio Environment Using Channel State Information," *IEEE Access*, vol. 6, pp. 47 682–47 698, 2018.

[15] Z. Wei, F. Liu, C. Masouros, N. Su and A. P. Petropulu, „Toward Multi-Functional 6G Wireless Networks: Integrating Sensing, Communication, and Security," *IEEE Communications Magazine*, vol. 60, no. 4, pp. 65-71, April 2022.

[16] Y. Polyanskiy, "A Perspective on Massive Random-Access," *IEEE International Symposium on Information Theory (ISIT)*, pp. 2523-2527, 2017.

[17] N. Abramson, "The ALOHA System: Another Alternative for Computer Communications," *Fall Joint Computer Conference, vol. 37,* pp. 281–285, 1970.

[18] E. Paolini, G. Liva, and M. Chiani, "Coded Slotted ALOHA: A Graph-Based Method for Uncoordinated Multiple Access," *IEEE Transactions on Information Theory, vol. 61, no. 12, pp.* 6815–6832, Dec. 2015.

[19] A. Fengler, P. Jung, and G. Caire, "SPARCs for Unsourced Random Access," *IEEE Transactions on Information Theory*, vol. 67, no. 10, pp. 6894–6915, Oct. 2021.

[20] F. Clazzer, C. Kissling, and M. Marchese, "Enhancing Contention Resolution ALOHA using Combining Techniques," *IEEE Transactions on Communications,* vol. 66, no. 6, pp. 2576–2587, Jun. 2018.

[21] S. Kaul, M. Gruteser, V. Rai, and J. Kenney, "Minimizing Age of Information in Vehicular Networks," *IEEE International Conference on Sensing, Communication, and Networking (SECON)*, pp. 350-358, June 2011.

[22] S. Kaul, R. Yates, and M. Gruteser, "Real-time Status: How Often Should One Update?" *IEEE International Conference on Computer Communications (INFOCOM)*, pp. 2731-2735, 2012.

[23] Y. Sun, Y. Polyanskiy, and E. Uysal, "Sampling of the Wiener Process for Remote Estimation over a Channel with Random Delay," *IEEE Transactions on Information Theory,* vol. 66, no. 2, pp. 1118–1135, 2020.

[24] R. D. Yates, Y. Sun, D. R. Brown, S. K. Kaul, E. Modiano, and S. Ulukus, "Age of Information: An Introduction and Survey," *IEEE Journal on Selected Areas in Communications,* vol. 39, no. 5, pp. 1183–1210, 2021.

[25] G. Mergen and L. Tong, "Type Based Estimation Over Multiaccess Channels," *IEEE Transactions on Signal Processing,* vol. 54, no. 2, pp. 613–626, Feb 2006.

[26] V. Ulitzsch and J.-P. Seifert, "Breaking the Quadratic Barrier: Quantum Cryptanalysis of Milenage, Telecommunications' Cryptographic Backbone" *Cryptology ePrint Archive*, 2022

[27] J. Dommel, Z. Utkovski, O. Simeone, and S. Stańczak, "Joint Source-Channel Coding for Semantics-Aware Grant-Free Radio Access in IoT Fog Networks," *IEEE Signal Processing Letters,* vol. 28, pp. 728–732, 2021.

[28] P. Veron, "Code Based Cryptography and Steganography," *Lecture Notes in Computer Science*, vol. 8080, Springer, Berlin, 2013.

[29] T. V. Benzel, C. E. Irvine, T. E. Levin, G. Bhaskara, T. D. Nguyen, and P. C. Clark, "Design Principles for Security," *Naval Postgraduate School Monterey Ca Dept of Computer Science*, Technical Report, 2005.

[30] Z. Utkovski, P. Agostini, M. Frey, I. Bjelakovic, and S. Stańczak, "Learning Radio Maps for Physical-Layer Security in the Radio Access," *IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, pp. 1–5, 2019.

[31] V. Ulitzsch, S. Park, S. Marzougui, J.-P. Seifert: "A Post-Quantum Secure Subscription Concealed Identifier for 6G." *Conference on Security and Privacy in Wireless and Mobile Networks (WISEC),* pp. 157-168, 2022.

[32] L. Sun and Q. Du, "A Review of Physical Layer Security Techniques for Internet of Things: Challenges and Solutions," *Entropy*, vol. 20, no. 10, 2018.

[33] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, "6G Wireless Networks: Vision, Requirements, Architecture, and Key Technologies," *IEEE Vehicular Technology Magazine*, vol. 14, no. 3, pp. 28–41, 2019.

[34] P. Popovski, O. Simeone, F. Boccardi, D. Gündüz, and O. Sahin, "Semantic- Effectiveness Filtering and Control for Post-5G Wireless Connectivity," *Journal of the Indian Institute of Science*, vol. 100, p. 435–443, May 2020.

[35] A. Aijaz, "Private 5G: The Future of Industrial Wireless," *IEEE Industrial Electronics Magazine*, vol. 14, no. 4, pp. 136–145, 2020.

[36] D. Rafique and L. Velasco, "Machine Learning for Network Automation: Overview, Architecture, and Applications [Invited Tutorial]," *Journal of Optical Communications and Networking*, vol. 10, no. 10, pp. D126–D143, 2018.

[37] Y. Ji, J. Zhang, Y. Xiao, and Z. Liu, "5G Flexible Optical Transport Networks with Large-Capacity, Low-Latency and High-Efficiency," *China Communications*, vol. 16, no. 5, pp. 19–32, 2019.

[38] B. Shariati, et al., "Demonstration of Latency-Aware 5G Network Slicing on Optical Metro Networks," *Journal of Optical Communications and Networking (JOCN)*, vol. 14, no. 1, pp. A81-A90, Jan 2022.

[39] G. E. P. Box, "Robustness in the Strategy of Scientific Model Building", *Robustness in Statistics*, Academic Press, pp. 201–236 ,1979.

[40] C. De Lima et al., "Convergent Communication, Sensing and Localization in 6G Systems: An Overview of Technologies, Opportunities and Challenges," *IEEE Access*, vol. 9, pp. 26902-26925, 2021.

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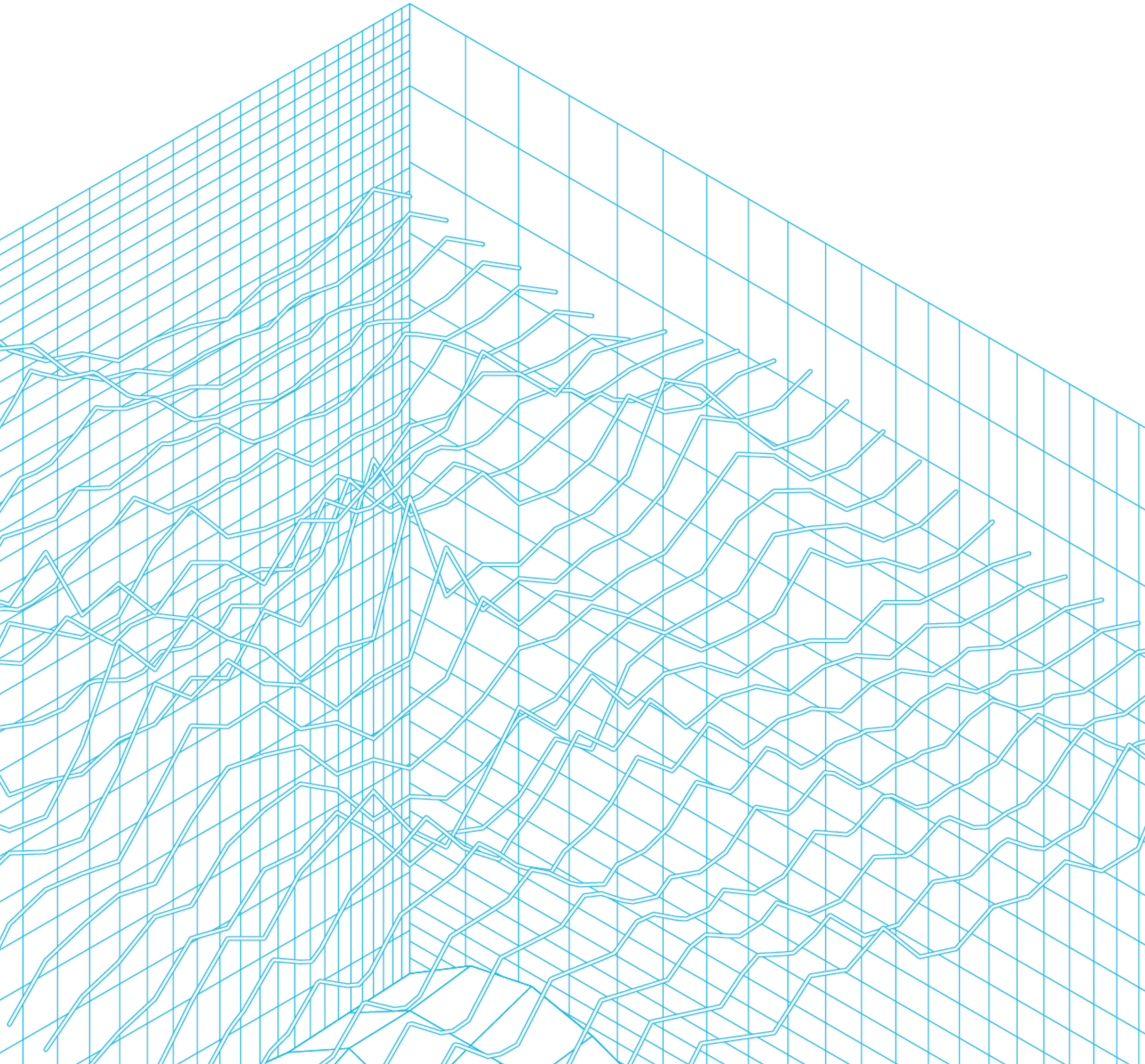

6G kWh