6G Requirements and Design Considerations

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6G REQUIREMENTS AND DESIGN CONSIDERATIONS

by NGMN Alliance e.V.

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EXECUTIVE SUMMARY

In this publication, the NGMN Alliance builds on its earlier work and sets out important aspects for network evolution, considering the opportunities, challenges and design objectives that are intended to guide the broader industry towards delivering services valued by end users. The objectives of this work have been to explore design requirements and provide timely guidance to the industry, to play a key role in avoiding fragmentation of 6G standards and ecosystem to achieve affordable deployments, and to engage with different stakeholders, monitor external 6G activities and facilitate timely exchange with external organisations.

This contribution serves to offer guidance towards the realisation of the vision of communication systems for 2030 and beyond, currently being developed by ITU-R. As the community builds consensus around potential trends, use cases and associated capabilities, it becomes imperative to prioritise design considerations in all aspects, from research and innovations to implementation, deployment, and operational models. In general, the foundation from which this contribution has been developed is on the understanding that there will be a graceful evolution towards 6G, and at this stage we do not rule out the possibility that 6G is an evolution of 5G, either for the core network, the RAN, or both.

The requirements include a set of essential needs related to network evolution, such as digital inclusion, energy efficiency towards containment of the overall network energy consumption, and environmental sustainability, as well as the capabilities associated with the prospective generic use cases defined in earlier NGMN publications [1], [2] and highlighted in Section 3. In addition, the overall conditions related to the introduction of new service creation must be considered.

We recommend that research, and the development of future ecosystems, should prioritise the key challenges to address societal and environmental needs, including well-being, prosperity, sustainability, security, resilience and inclusion. In addition, further enablement of digital transformation and automated industries is expected to advance, to address future market needs, with expanded and differentiated opportunities, operational efficiency, and economic sustainability.

A number of design attributes and requirements are to be addressed. The outcome sought is obviously one in which end user benefits are identified at a cost which is acceptable. The challenge to reduce cost per bit will however remain. New approaches are needed in addition to continued efforts on simplification, energy efficiency and automation. End to end intelligent system automation, visibility / traceability, and efficient management are needed targeting sustainable and flexible deployment and simplified operation. New paradigms are needed to address traffic growth, extreme requirements (such as immersive, critical, massive, native), capacity needs, minimisation of added complexity, and the alternatives to densification, considering the practical limits of wide-area mobile systems. Service versatility must be provided where and when applicable and relevant; all capabilities may not be concurrent or provided simultaneously. In addition, the use cases with extreme requirements are expected to be enabled where and when needed by the befitting solution and access mechanism. There must be flexibility to make trade-offs for deployment. In co-existence and potential concurrence of services such as those related to communication, computing, sensing and AI, there is a need to consider efficient optimisation of resources and interactions, in addition to privacy, data protection, data ownership and sensitivity, local-offload trade-offs, power constraints and energy efficiency. Moreover, 6G should be designed with novel services and devices, which can validate and accelerate the necessity of future mobile networks for the end users. Finally, 6G should also be engineered to help operators meet the net-zero objectives that many of them have committed to, among other environmental sustainability targets.

The 6G system is expected to be built upon the features and capabilities introduced with 5G, alongside new capabilities, to deliver new services and value. The essential needs are particularly directed towards building networks that deliver digital inclusion, that are environmentally and economically sustainable, that reduce complexity, address traffic growth, and enable new services through additional features that are complementary to mobile networks.

The views of the NGMN indicate that for a fundamental change to take place there must be significant benefits that justify the cost and complexity in technology migration. In any migration to 6G the transition should be carefully considered to ensure that 5G networks are not compromised, and that the features provided by 6G provide end-user value through the addition of new features or the ability to reduce operational cost and subsequently affordability.

A healthy global ecosystem, including interdisciplinary research and innovations, and global standardisation, will be essential to address the drivers of 6G, along with design requirements on a graceful path.

CONTENTS

01 INTRODUCTION

The Next Generation Mobile Networks (NGMN) Alliance's goal is to **provide impactful guidance to achieve innovative and affordable mobile telecommunication services for the end user.**

Founded by mobile network operators and with global membership, it operates an open forum to discuss and provide direction on next generation network infrastructure.

A particular focus for NGMN's members and partners is the transition towards 6G and associated with this topic NGMN has previously published the following: 6G Drivers and Vision [1] and a 6G Use Cases and Analysis [2].

In this publication, the NGMN Alliance builds on its earlier work and sets out important aspects for network evolution, considering the opportunities, challenges and design objectives that are intended to guide the broader industry towards delivering services valued by end users.

It is intended that this publication offers guidance towards the realisation of the vision of communication systems for 2030 and beyond, currently being developed by ITU-R. As the community builds consensus around potential trends, use cases and associated capabilities, it becomes imperative to prioritise design considerations in all aspects e.g. research, technology innovations, implementation, deployment, and operational models to support these use cases and associated capabilities.

1.1 CONTEXT

The 5G networks, designed to meet the demands set by IMT-2020, are gaining broad adoption world-wide. A combination of an advanced wireless system built upon the 5G-NR interface, new network capabilities associated with the 5G core, and a new architecture using cloud-native approaches are enabling high-performance networks to be dynamically deployed, with distributed intelligence to the edge, and end to end automated orchestration to address specific user needs. Several features and capabilities of 5G and its evolution are intended to make 5G networks future-proof, as the industry advances in its journey forward and studies on future 6G systems are being developed worldwide.

Given 5G is at an early stage in its life cycle and new business models of 5G are yet to be fully commercialised, and uptake in various segments, such as private and industrial applications is still to grow to a significant scale, the approach towards setting requirements for 6G remains somewhat fluid. It is not yet clear what would be required of an entirely new 6G technology or how it can advance societal and user needs above and beyond 5G and its evolution, so it is worth noting that the motivations, potential use cases and their implications on potential requirements for mobile systems in the 2030s outlined in this document are to be considered without distinction between whether those apply to any new 6G technology, an evolution of 5G / 5G Advanced or a combination thereof.

This publication has been developed on the understanding that there will be a graceful evolution towards 6G, and at this stage we do not rule out the possibility that 6G is an evolution of 5G / 5G Advanced, either for the core network, the RAN, or both.

1.2 DOCUMENT STRUCTURE

As outlined above, the NGMN Alliance has previously published reports related to 6G Vision and Use Cases. These activities were conducted in parallel with recognised ongoing technology innovations, building blocks, and developments related to spectrum and regulation.

This publication is closely aligned to requirements, however the NGMN recognised that it is premature to define quantitative measures that define 6G whilst service characteristics and service demands remain unclear. Therefore, this publication focusses on qualitative indicators and high-level design considerations.

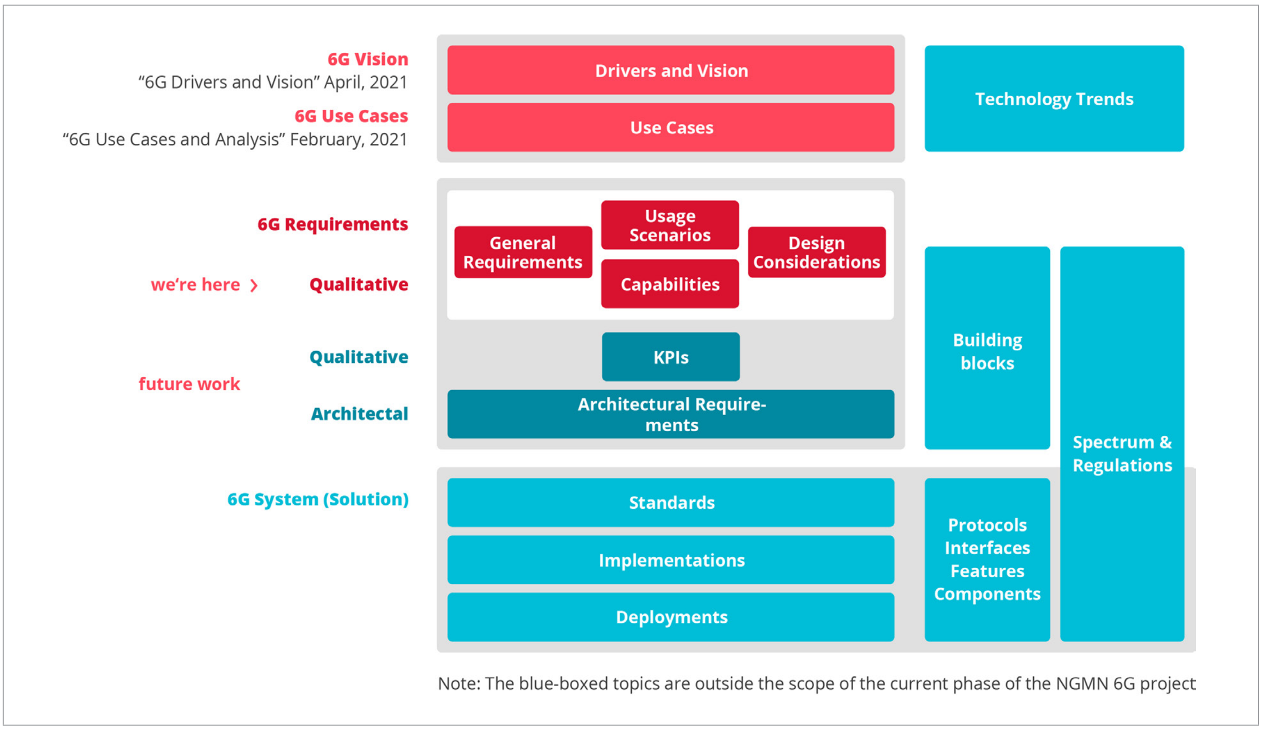

Figure 1: Positioning of this publication in the broader NGMN 6G Programme and sections covered within this publication

The structure of this document reflects the highlighted (dark red boxes) in Figure 1.

Section 2 defines the motivations for this work; Section 3 reviews the use cases and the capabilities sought; Section 4 introduces general requirements associated with the usage; Section 5 introduces design considerations including recognised challenges and trade-offs.

Finally, Section 6 offers the conclusions and proposed way forward.

02 MOTIVATION AND SCENE SETTING

The motivation for this study and the corresponding description for 6G design requirements follows a long-standing trend in the industry to review mobile network capabilities on a regular basis, and where appropriate, to set target outcomes that meet new and emerging societal and user needs. Previous generations have been introduced on a decade-long cycle, and with the last significant generation change being introduced to meet the demands for IMT-2020 it is time to consider the needs and requirements for connectivity and communication for IMT system for 2030 and beyond.

The NGMN Alliance commenced their 6G Project by setting out an outline vision which was then followed by an extensive review of potential use cases proposed by many partners from industry and research communities. In this new work, NGMN were invited to contribute network design requirements, along with key capabilities, new or expanded, that would need to be available to enable prospective use cases.

Whilst conducting this work, there was an emerging view amongst the NGMN that 6G is used to define a system solution that supports a broad range of use cases and use cases. As a result, 6G is best described as a non-unique system that builds upon the global harmonised standards for mobile networks and may include complementary components and differing implementations, selected to deliver capabilities that meet operational needs depending on specific deployments.

Regardless of the complementary components that are less well defined, the importance of global standards is recognised as being of continued critical importance to achieve global economies of scale. The standard development organisations (SDOs) will therefore play a central role in ensuring the delivery of uniform products into the market that are based on common specifications. It is anticipated that the 3rd Generation Partnership Programme (3GPP) will continue to specify the mobile radio, service, and system aspects that are adopted by SDOs.

The complementary components and different deployments reflect the use of specifications from other organisations when appropriate (e.g. IETF and O-RAN), and that 3GPP specifications support diverse implementation (e.g. virtualised vs. non-virtualised), and different deployment approaches (including non-terrestrial deployment in the 6G era).

Similarly, requirements are not only directly driven by the user. Network operator and service provider demands to improve network and service performance as well as increased efficiencies in value creation and delivery must also be considered. Therefore heterogeneity of potential uses and deployment environments necessitates service and solution versatility to maximise flexibility and enable design trade-offs.

In summary, the objectives of this publication have been,

- To explore design requirements, highlight network operators' perspective and provide timely guidance to the industry.
- Play a key role in avoiding fragmentation of 6G standards and ecosystem to achieve affordable deployments.
- Develop requirements by taking a user centric view.
- Engage with different stakeholders, monitor external 6G activities and facilitate timely exchange with external organisations.

In the following section a recap of the Use cases as identified by NGMN members and partners is introduced.

03 POTENTIAL USE CASES

ENHANCED HUMAN COMMUNICATION	ENHANCED MACHINE COMMUNICATION	ENABLING SERVICES	NETWORK EVOLUTION
XR immersive holographic telepresence communication	Robot Network Fabric	3D hyper-accurate positioning localization, and tracking	Trusted Native AI – AIaaS
Multi-modal communication for Teleoperation	Interacting Cobots	Interactive mapping, digital twins & virtual worlds	Coverage expansion
Intelligent interaction: sharing of sensation, skills & thoughts		Automatic detection protection & inspection	Energy Efficiency
		Digital healthcare	
		Smart Industry	
		Trusted composition of services	

Figure 2: Use Case Classes and Potential Generic Use Cases

As outlined in NGMN 6G Use Cases and Analysis [2], use cases have been grouped into four classes of Generic Use Cases based on their key common characteristics as illustrated in Figure 2, it should be noted that any use cases could appear in multiple classes.

The NGMN Alliance recognises the ongoing development of the IMT Vision for 2030 and beyond and has actively contributed input including use cases to ITU-R during this process.

The expected scenarios for 6G are represented by NGMN from a variety of perspectives, though with fundamental similarities. These representations highlight in different ways or combinations, the key communication aspects of classes of generic use cases, such as immersive. They also include use cases expected to empower communication, such as integrated intelligence or sensing, and the end to end targets such as sustainability and inclusion.

It is acknowledged by the NGMN that identification of future 6G services is still at an early stage and the proposals are speculative. It is understood that the 6G services proposed will need to be analysed in terms of their alignment with market demands and relevance before engaging into specifying the associated formal requirements in standards.

In the following section, a qualitative review of the requirements is introduced for these services without drawing conclusion on how these are most economically delivered.

Enhanced Human Communication

including use cases that have the potential to enrich human communications, such as immersive experience, telepresence & multi-modal interaction.

Enhanced Machine Communication

including use cases reflecting the growth in collaborative robotics, and autonomous machines, the requirement for sensing the surrounding environment and the need for robots to communicate among themselves and with humans.

Enabling Services

to support new use cases through additional features such as high accuracy location, mapping, energy efficiency or body sensing data.

Network Evolution

describing aspects related to the evolution of overarching technologies including AI as a service, energy efficiency, and delivering ubiquitous coverage.

04 REQUIREMENTS AND VALUE INDICATORS

There are fundamental properties of mobile networks which are deployed to deliver wide area mobile services to meet objectives on key criteria such as coverage, speed, latency and area capacity. These performance criteria will be expected to improve with 6G to address new uses cases and use cases, with the corresponding design implications introduced in Section 5.

The requirements are introduced in this section in three parts: the first part introduces a set of essential needs related to network evolution; the second introduces the capabilities associated with the proposed use cases defined in Section 3, and the third describes overall conditions related to the introduction of new service creation.

4.1 ESSENTIAL NEEDS FOR NETWORK EVOLUTION

When considering the communication system needs in 2030 and beyond the NGMN identified a set of 6G features that are essential. These features are not necessarily driven by new or speculative use cases but reflect essential needs when operating public networks.

4.1.1 DIGITAL INCLUSION

Everyone should be able to access digital services with a good level of service quality and in an economically accessible way. This leads to the following guidance:

- 6G Design should be designed to enable coverage of sparsely populated areas in an economically viable way.

- User interfaces to 6G should be simple and support intuitive interactions.

- Digital inequity of 6G services should be avoided.

4.1.2 ENERGY EFFICIENCY

Energy efficiency, when measured by energy consumed per transmitted volume, has improved by several orders of magnitude since the introduction of mobile networks. However, the volume of data transported has increased at a greater rate which means that the total energy consumed has increased over time. This negatively impacts the environmental sustainability of networks, adds cost to operations, and threatens the ability for networks to continue to scale to meet future capacity demand. In addition, many operators have made strong commitments[1] regarding reaching carbon neutrality and net-zero carbon emission, during the 6G-era. This leads to the following guidance:

- Improvements in energy efficiency must continue to be sought for 6G, and the improvements delivered should exceed the forecast growth in traffic volume to reduce overall energy consumption.

- To support this, energy consumption figures need to be comparable and interoperable between equipment suppliers and must be made available at all levels of the system to enable 6G system wide monitoring and optimisation.

- Network features should be supported for low energy consumption of end user devices, and energy scavenging for IoT devices.

4.1.3 ENVIRONMENTAL IMPACT

Service providers are increasingly being measured on their Environmental, Sustainability, and Governance (ESG) performance. Metrics associated with environmental reporting are classified in four themes: climate change, natural resources, pollution and waste, and environmental opportunities. Service providers are expected to report not just on their own impact but those of their

[1] GSMA Report "Mobile Net Zero – State of the Industry on Climate Action 2022" https://www.gsma.com/betterfuture/wp-content/uploads/2022/05/Moble-Net-Zero-State-of-the-Industry-on-Climate-Action-2022.pdf

supply chain reflecting the products that are purchased and consumed. Therefore, beyond the energy efficiency guidance provided in the previous section the overall environmental impact of 6G should be minimised. This leads to the following guidance:

- A base station that includes 6G should be able to record and, if needed, adapt its RF emission levels, including number of beams, beam occupancy and radiated power, to enable it to follow any given RF profile, e.g., to demonstrate compliance relative to national guidelines for EMF or for spectrum licensing compliance.

- Resources consumed during the manufacturing of network equipment and terminals should be monitored and reported as required.

- Greenhouse gas emitted over the complete life cycle e.g., manufacture, operation to end of life of network equipment and terminals should be able to be monitored.

- The impact of real-estate assets e.g., antenna structures, equipment cabinets, data centers, and their resource consumption should be able to be monitored.

- Common indicators should be sought in 6G design to allow comparison and to ease the elaboration of the environmental impact of 6G-based services.

4.1.4 NATIVE TRUSTWORTHINESS

Public telecommunication networks are part of critical national infrastructure and the services they deliver are increasingly critical for many daily activities. This is driving a sharper focus on native trustworthiness.

An often used definition of trustworthiness is from the National Institute of Standards and Technology (NIST), which includes the following five aspects: security (including confidentiality, integrity, availability), privacy, reliability, resilience, and safety[2].

Native trustworthiness should be specified to ensure that the system is protected from unintended and unauthorised access, that personal data and sensitive network data is protected, the system delivers stable and predictable performance in expected conditions, the system gracefully returns to predictable performance in the event of unexpected conditions, and that the system operates safely with respect to life, health, property, or data of telecommunication system stakeholders and the physical environment.

6G needs to support trustable networking environments even in untrusted multi-party ecosystems. This means 6G must support guaranteed service and data availability, security, and privacy across multi-party infrastructures, including the establishment of trusted exchanges across untrusted environments.

Guidance related to native trustworthiness include the following but not limited to:

- The 6G design should provide means to ensure high levels of resilience, security, safety, reliability, and privacy.

- The 6G system should be quantum robust in face of the introduction of quantum computing.

- Digital identities should be protected and securely stored to prevent from unauthorised access.

- Privacy sensitive data should be protected not only in terms of confidentiality, integrity and availability but also anonymity as well as according to the minimality principle[3].

- The 6G system should include security assurance schemes for the whole lifecycle from the products design to network deployment and operation.

[2] NIST Framework for Cyber-Physical Systems; Volume 1, Overview

[3] The minimality principle means that sensitive data should be disclosed to a minimum possible extent for a minimum period of time only to entities authorized by the user and to be used only for purposes explicitly authorized by the user.

4.1.5 SUPPORT FOR REGULATED AND PUBLIC SAFETY SERVICES

Consistent with and implicit in usage scenarios, native voice services must be available at the launch of 6G network equipment and user terminals. Voice communication conveys emotions and personality, enriching the actual content of the data and information. Mobile voice services are real-time critical services, so the slightest delay or interruption are noticeable to the user. Enabling seamless and high-quality voice calls across multiple generations of radio access requires intricate network design and must be part of 6G fundamental requirements. 6G networks will co-exist with 5G networks for a long time, so inter-working and hand-off with 5G voice services must be supported to provide continuity and a smooth transition to 6G.

Messaging services have become integral to everyday life, from social interactions to business applications. While the technical implementation of messaging service(s) is transparent to the consumer, support for interoperable message services is needed.

It is imperative that national and regional regulatory requirements be supported at the launch of the next generation of mobile networks. Emergency services still require support for voice communications.

4.1.6 AUTOMATION OF END TO END SERVICE DELIVERY

Network operators will have to offer a larger and more complex portfolio of services to provide their customers the best fitted services for their needs at the time they need it. An ability to dynamically provide and dynamically adapt services tailored to the exact needs of customers is required to manage the tradeoff between added value for customers and cost. But managing the associated rising complexity is a challenge by itself. In this context, automation of service delivery is critical for network operators to enable them to efficiently manage large portfolios of services and will allow them to:

- Optimise the time required to deliver a custom service.
- Reduce the risk of erroneous configuration instruction and associated side effects.
- Manage dynamically adaptive networks, for example to adapt to changing customer demand or evolution of network topology.

Such ability to automate service delivery implies that 6G Networks are capable of:

- Full-system standardised monitoring to enable the collection of the required data to feed automation algorithms.
- Support different configurable trade-offs between several possible optimisation objectives (e.g., energy consumption, capacity, resilience) and be able to switch between them depending on the context.
- Support a standardised or at least uniform service description framework.
- Provide flexible and configurable network functions at the access and core layers.

4.1.7 AUTOMATED NETWORK PROGRAMMABILITY

The programmability of concatenated resource segments is foundational for a system-wide automation of end to end network slicing, with dynamic adaptability to system conditions, service assurance and life-cycle management, without human intervention.

An automation of end to end network slicing is essential for the realisation of new capabilities and services being envisioned for 6G. In this context, resource allocation for a given end to end network slice spans the different segments of core, edge, transport, with heterogeneous coverage footprints, which reflect various deployment scenarios.

With the continuing emergence of innovative services, and flexible deployment scenarios, architectural shifts are pivotal for an effective management of the IP bearer network and resource allocation across the different segments of an end to end system. A concatenated routing of resources, across the different segments of an end to end system, for a given end to end network slice, augments the granularity of the programmability of the bearer network.

The primary benefits that accrue from a self-organising automation of a concatenation of resource segments, include compatibility with existing networks, heterogeneous cloud networks, agility of service provisioning, ubiquitous connectivity, deterministic quality, and an improved granularity of resource allocation, through service awareness. These attributes are aligned with optimised performance, extensibility, and scalability for enabling evolutionary business and deployment models, over flexible modalities of end to end network slicing.

4.1.8 ARTIFICIAL INTELLIGENCE AND COMPUTE RELATED CAPABILITIES

The ability to provide AI as a service (AIaaS) is seen as a new enabler for the 6G system. In this perspective, AI-based applications could be hosted and taken care of by the 6G system, which will provide:

- Communication services between intelligent agents well suited for AI requirements.
- Computing power to efficiently host AI-based applications.

A 6G system should benefit AI applications thanks to its ability to support large AI models, to ease training with its data sharing capabilities and to support large scale distributed learning. As a consequence, a 6G system should speed up delivery of reliable and accurate inference results while protecting data privacy and sovereignty. In addition, a 6G system is expected to provide superior energy efficiency compared to classical implementations.

This perspective will require specific capabilities to be supported by 6G systems:

- The volume of training / updating data to exchange between intelligent agents could be massive, especially for large scale distributed learning deployment. Consequently, AIaaS requires high uplink traffic capacity.
- Collected and storage training data can be sensitive and need to be processed with privacy and transparent handling.
- For AI applications with stringent end to end latency requirements, end to end latency includes both communication and inference computing time. Such applications need highly efficient and reliable results in terms of inference capability of AI and its delivery.
- A 6G system should support the ability to manage model training / updating, model deployment, and model storage, and to facilitate model download.
- A 6G system should support the ability to manage and coordinate AI capable computing resources.

Careful design is necessary to ensure that the increase in volume of data does not lead to unbounded energy increase that conflicts with the objective of reducing energy consumption.

4.2 POTENTIAL NEW CAPABILITIES RELATED TO USAGE SCENARIOS

In this section the design considerations related to the three proposed usage scenarios, enhanced human communications, enhanced machine communications, and enabling services, introduced in Section 3, are discussed.

As outlined in NGMN's 6G Use Cases and Analysis publication [2] use cases have been grouped into four classes of generic use cases based on their key common characteristics, though the use cases may not necessarily be restricted to one class.

Each class is further discussed below, in terms of potential requirements and challenges.

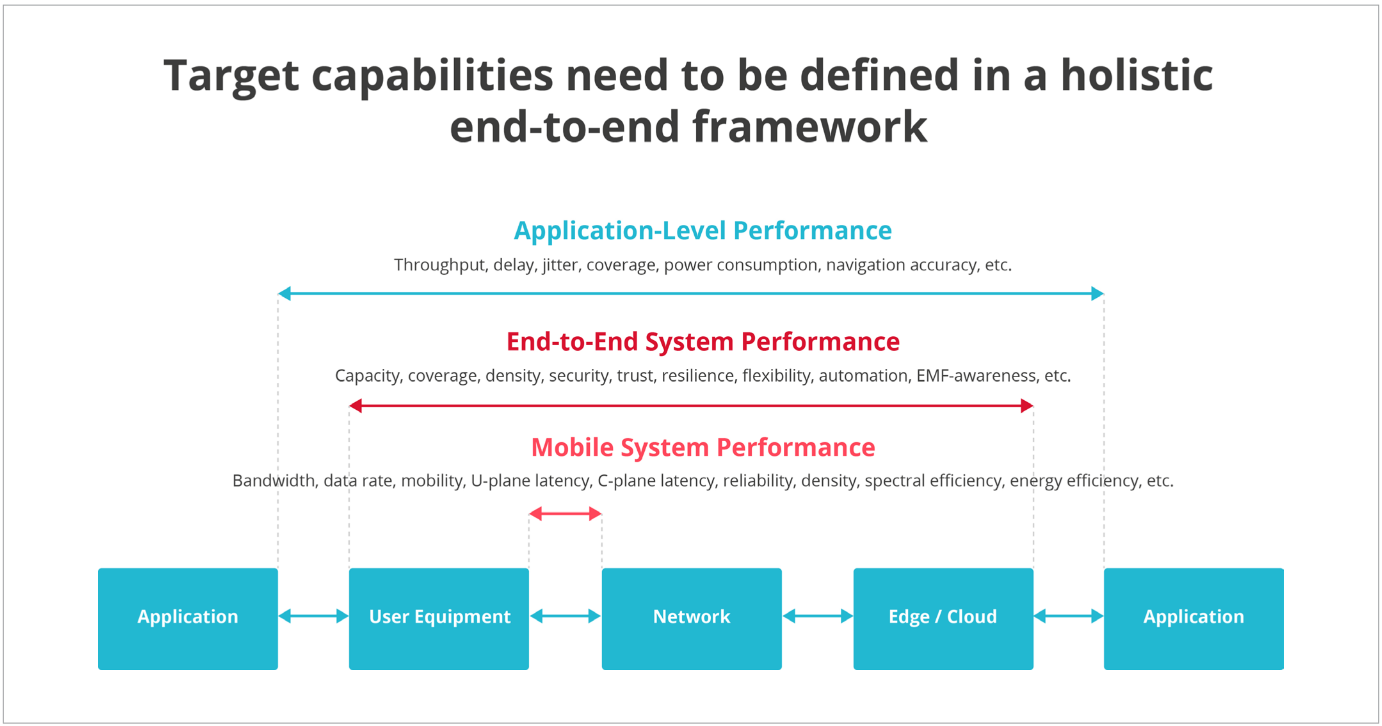

Figure 3: Different levels of value Indicators

4.2.1 GENERAL ANALYSIS

The capabilities to enable potential 6G use cases are expected to include both expanded ones, such as those for throughput and latency, and new ones, such as value indicators related to sensing and imaging or AI inference. The identification of meaningful capabilities for 6G has generally taken a user or application-level perspective, with considerations for the end to end system-level performance. In this context, sub-network considerations, particularly for radio / access are highlighted as appropriate. Figure 3 shows a perspective on different levels of value indicators.

At this stage, the capabilities are discussed qualitatively, and those which may be positioned as quantitative are limited to identification of indicators, possibly along with representation units.

4.2.2 ENHANCED HUMAN COMMUNICATIONS

This grouping represents applications that have the potential to enrich human communications, such as immersive experience, telepresence, and multi-modal interaction. Within this group there is a range of proposed applications. Some complement the existing real-world experience (extended or augmented reality) for applications such as remote health, teaching, or tourism. Others are more immersive (virtual reality) which may support applications related to gaming, training in complex environments, or fully hosted communications in a virtual world.

Whether the applications are augmented reality, or fully immersive virtual reality, it is likely that the system supports multi-modal / sensorial communication with multiple inputs and multiple outputs that are further enhanced with ambient sensor data. Such applications typically require high user experienced throughout, human-acceptable latency, and synchronicity between devices. In most cases it is expected that the system includes wearable devices which may, in themselves, have limited communication capabilities. The dependency on private data implies that appropriate authentication mechanisms are supported with credentials securely stored and protected.

The characteristics demanded for a specific application will differ depending on the level of 'immersiveness' that is anticipated. For example, an augmented reality service based on textual and symbolic information may have relatively modest data throughput and latency demands, whilst a fully immersive experience based on high-resolution 3D projection may require very low-latency communications to a local edge compute platform that performs image rendering.

The design requirements of a system are therefore specific for the intended application. The design should consider:

- Mobility requirements: How is the application intended to be used – is mobility necessary (or possible), or is the application going to be used within a controlled, localised, area?
- Connectivity Requirements: Will the application require wearable devices and if so, will these communicate through a gateway (such as a smart-phone or a local wireless hub) or will they require connectivity directly to a public mobile network?
- Compute Requirements: Will an edge compute platform be close to the usage of the application (e.g. a high-end graphical processing unit) to support dedicated image processing and reduce latency?
- Trustworthiness Requirements: What level of trustworthiness is desired – is reliability, security, and resilience an important factor for the specific application?
- What are the cost implications, the overall value and end-user propensity to pay for a service over a public mobile network relative to a service provided over alternative (combination of) technologies?
- Environmental Interaction Requirements: How much and what level of interaction with the real world is desired for the specific use case e.g. immersive experience, telepresence or multi-modal interaction?
- Some applications of immersive communication are susceptible to be largely adopted and widely used among 6G subscribers. What capacity is required from the 6G system to support the envisioned (potentially large) numbers of simultaneous users of an immersive application?

Depending on the application, the throughput demanded to the end device (smart-glasses or immersive headsets) could be anywhere from a several Mbps to Gbps and different applications will also have its own sensitivity to latency and jitter. It therefore appears that a single quantitative approach is inadequate to cover this set of use cases as solutions will be designed for a given purpose. With this understanding, it is more appropriate to consider 6G as a set of capabilities which reflect the combination of complementary technologies and connectivity options that are necessary to support such applications.

4.2.3 ENHANCED MACHINE COMMUNICATIONS

The flexible deployment options and high level of security and performance have established 5G as a solution for a variety of connectivity solutions within an industrial setting. This developing eco-system builds upon the economies of scale that are driven by consumer mobile broadband enabling a supply of network equipment and end user devices that are cost optimised. It is anticipated that as this eco-system develops further in the period to 6G there will be a set of new demands associated with enhanced machine communication. This set of use cases reflects the growth in collaborative robotics, autonomous machines, the requirement for sensing the surrounding environment and the need for robots to communicate among themselves and with humans.

It can be foreseen that the system solution for such a use case is complex. A connected robot or machine will use sensors associated with its specific function, the processing of information may be conducted locally on the machine to support near real-time reaction, or a subset of data (or possibly all data) collected may be transferred to an edge compute node for more complex processing. The machine or robot may be in a fixed location, or in some cases it may follow a self-determined route in a factory environment.

Further, delivery robots that operate beyond an enclosed industrial environment can also be anticipated. In such cases, robots will require to sense the local environment, have good location and positional awareness, and have computational support either locally or at the edge of a mobile network to make decisions on route management and obstacle avoidance reflecting the safety of humans in the surrounding environment.

The 6G solution must therefore be able to adapt to the different use cases and environments in which the specific machine communication application is intended and to coexist with already existing 5G industrial deployment. The design should consider:

- Mobility requirements: How is the application intended to be used – is mobility necessary (or possible), or is the robot going to be used within a controlled, localised, area? If the robot or machine operate at a fixed, or near-fixed location, complementary solutions to a public mobile network may be appropriate.

- Compute Requirements: Is the processing of data performed locally on the machine to support real-time reaction, or at an edge compute platform?

- Trustworthiness Requirements: What level of trustworthiness is desired? Are reliability, security, and resilience an important factor for the specific application?

- Environmental Interaction Requirements: How much and what level of interaction with the real world is desired for sensing the surrounding environment?

Similar to the observations on enhanced human communications, it can be anticipated that the demands on a machine or robot application can vary enormously. At one extreme the data payloads and requirements on throughput and latency may be relatively modest. At the other extreme, a highly automated industrial process may require communication links that support Gbps rates, very low latency, and high resilience. Such process could also require the support of many simultaneously connected machines. However, it is essential to understand how the most extreme demands are best served with a 6G system when considered holistically to avoid specifying characteristics that may compromise other aspects. This is discussed further in Section 5 where trade-offs in system design are considered.

4.2.4 ENABLING SERVICES

In previous work on determining 6G use cases, NGMN and external stakeholders identified a category representing services that require additional features to communication networks, such as high accuracy location, mapping, environmental or body sensing data. Such features were previously outside the normal scope of defining communication networks. The following summarises the main groupings and associated design considerations.

Accurate 3D positioning, interactive mapping, object sensing and digital twins
In developing use cases, several were observed to have dependencies on accurate positioning. This includes a variety of devices, indoor and outdoor, covering low-cost objects such as autonomous tags to collaborative robots (cobots). The emergence of 'digital twins' that replicate aspects of the real-world, such as smart-cities, also have a need to collect a variety of 3D positioning data representing map location and height.

One proposal to complement conventional positioning solutions is to use combined sensing and communications technologies. In this approach, a modified radio protocol is proposed that uses reflections from objects to support sensing of the local environment. Such a capability may have applications where vehicles, machines, or cobots are required to both detect and communicate with each other and relative position is important.

The collection, transfer, and management of positioning, mapping sensing and imaging data introduces new requirements beyond those of 4G and 5G positioning. Solutions must be available that enable the capture of 3D positioning (indoor and outdoor), mapping sensing or imaging data; there must be sufficient capacity, throughput, and adequate latency in the communication network to support many location or position updates; the system must respect the principles of trustworthiness such that security mechanisms build end to end trusted exchanges of data and be compliant to local regulatory requirements.

Digital Healthcare
The healthcare sector is projected to have, in the future, new demands on technology and communication systems. This will include requirements that ensure that a hospital or health-care location has full connectivity across all building assets, ensuring that people and objects can all be connected over a robust trustworthy framework. Health monitoring and medical research will include in-body

devices that communicate with on-body devices outside, which in turn can transport the data to the internet where a digital body double is analysed. Such a6G telemedical paradigm will be enabled by body sensing and analytics in conjunction with wide area connectivity. The complexities of health-care management will be simplified using intelligent sensors, asset tracking, and workflow processes. In the broader sense, 6G system capabilities that host advanced computing platforms at the network edge may also be used to support image processing for diagnostic purposes and data management using AIaaS optimised for health sector needs.
The essential requirements of a 6G system include the ability to support sub-networks of body networks, and the need for privacy preserving technologies.

Smart Industry
The increasing automation of industry and manufacturing supported by digital technologies (often associated with industry 4.0) addresses not only direct production but also the whole business process. Within the production cycle there may be multiple processes that 6G systems can support with digital twinning enabling diagnostics, monitoring, and process optimisation.

The 6G system requirements will include the ability to collect data with high reliability, to integrate sub-networks and sensors, and to be able to process data on-site in a trustworthy framework. Where there is on-site enterprise compute infrastructure the 6G system capabilities may be hosted locally and interwork with a 6G system supporting wide-area coverage and mobility.

Trusted composition of services
It is anticipated that enhanced human and machine communication will increasingly require converged networks which will allow for a trusted composition of services to support the various, increasingly dynamic and complex use cases of the future.

This is expected to set requirements for the 6G system that provide a framework for a simplified and trusted composition of services by establishing a federated control-plane between different networks (mobile and fixed access, Bluetooth, Wi-Fi, ...). The control plane manages the needed service endpoints for service registration, discovery and pairing of user-plane functions.

4.3 SERVICE CREATION AND DELIVERY

As indicated, the trends point to a few classes of potential use cases and new enabling paradigms. The capabilities related to these enablers will likely develop and mature at different rates, therefore specific use cases may need a phased evolution.

The new forward-looking capabilities introduced as part of 5G Advanced are expected to evolve towards 6G extending the value associated with investments in 5G. In addition to feasibility and sustainability of service enablement and operation, a graceful evolution path creates stability in market. On the other hand, new features of 5G Advanced show that not all new use cases and services will be addressed at start of a new system. This must be considered in the development of 6G, while avoiding a short-term focused architecture to have the flexibility to introduce new features and use cases not imagined earlier in the development phase.

Service versatility must be provided where and when applicable and relevant; all capabilities may not be concurrent or provided simultaneously. In addition, the use cases with extreme requirements are expected to be enabled where and when needed by the befitting solution and access mechanism. There must be flexibility to make trade-offs for deployment. The reality is that a 6G network will not meet all performance goals and metrics for every subscriber at every location. In co-existence and potential concurrence of services such as those related to communication, computing, sensing and AI, there is a need to consider efficient optimisation of resources and interactions, in addition to privacy, data protection, data ownership and sensitivity, local-offload trade-offs, power constraints and energy efficiency.

05 DESIGN CONSIDERATIONS AND TRADEOFFS

With the general requirements related to network evolution and new capabilities introduced previously, this section identifies the significant design considerations to meet those requirements. General considerations are introduced, followed by more detailed guidance related to individual network and service aspects.

5.1 INTRODUCTION

Within the mobile radio network domain, the 5G Stand Alone (5G SA) is at an early stage of deployment with 31 network operators having launched 5G SA as of Q3 2022 [3]. It is anticipated that this will increase significantly in the following years as 123 network operators in 55 countries have demonstrated an intent to launch 5G SA [3]. This transition is motivated by several factors: improved spectrum efficiency and more effective usage of new spectrum bands, improved energy efficiency and improved capabilities related to end user performance such as throughput and latency. To support this, administrations in many regions identified and released allocations of new IMT spectrum.

The design for 6G may include the specification of a new Radio Access Technology (6G-RAT) but this is not yet assured and 6G becoming an evolution of 5G-NR cannot be discounted. Regardless, co-existence with 5G-NR will need to be supported. For a new 6G-RAT to displace 5G it must demonstrate very significant benefits over and above an evolved 5G-NR in the most significant metrics such as spectral and/or energy efficiency. The potential for a 6G-RAT should also be approached with a view on whether new IMT spectrum is identified, in what band, and what quantum of resource as this will determine whether an economic solution is appropriate for wide-area mobility.

If a 6G-RAT is deployed in a new IMT band, then it should complement existing 5G deployments and avoid any spectrum efficiency reduction of 5G. For a 6G-RAT to displace incumbent 5G technologies in existing spectrum bands the threshold for relative improvement over 5G-NR should be greater to overcome the additional cost and complexity associated with technology migration. During such a migration the 6G service should have access to 5G spectrum to ensure it offers competitive data rates to 5G, either using a dual connectivity architecture or, using dynamic spectrum sharing between 5G and 6G-RAT with a cost-effective shared baseband implementation. It should also be noted that as service providers continue to seek improvements in operational and energy efficiency, there is a desire for networks to become 'simpler' to operate and maintain, therefore 6G should not add complexity, while design paradigms should prioritise and ensure graceful introduction and easy operation. This means that the migration to 6G should avoid disrupting existing users and be software driven, taking advantage of concepts like virtualisation.

The 5G Core (5GC) that underpins 5G Stand Alone (5G SA) networks is at a similar stage of maturity and deployment to 5G SA. This is cloud-native with an open, modular structure, coupled with the 5G Service Based Architecture (5G SBA) making it practical to introduce and scale network functions as required. The 5GC SA functions can be moved to the edge of the network, satisfying the low latency demands of critical communication to fulfil the needs of new services and applications. For 6G, it is anticipated that the system architecture will inherit the same design principles ensuring a smooth evolution for new communication services.

Significantly, the emergence of disaggregated RAN principles on the access network is also leading to flexibility and new options in deployment through the disaggregation of network elements such as centralised and distributed units (CU and DU). In some cases core network functions, oriented to the needs of edge applications are deploying to more edge locations and the access and core networks are gradually appearing to overlap in physical locations. 6G should consider the convergence and reconfiguration of logical functions to deliver more efficient and lower cost deployments.

In parallel to the deployment of 5G networks there is a trend in many geographic regions towards separation of network assets by service providers, leading to tower assets being managed by providers that then offer wholesale access using either active or passive sharing. Other developments include the emergence of neutral hosts that install shared infrastructure to host multiple service providers. These commercial frameworks must be fully supported by 6G systems.

With this context and based on the requirements and new capabilities introduced previously, the following expands on the high-level system design considerations. Section 5.2 describes system architecture considerations and sections 5.3 to 5.6 discuss design considerations that relate to radio network design.

5.2 SYSTEM ARCHITECTURE CONSIDERATIONS

Multi access convergence
The essential, and new requirements will require a 6G system to support access to communication systems that extend beyond conventional cellular based infrastructure. In one extreme, 6G should be able to support very wide area and ubiquitous coverage, and at the other it should be able to support fully immersive communications in localised areas.

Building upon the inherited cloud and service-based architecture approach, it is anticipated that the evolved 6G architecture will introduce new network functions that extend core capabilities such as mobility management, routing, security, policy control, charging and subscriber data management to support seamless multi-access across disparate networks.

Cross-domain and cross-layer scheduling and management
For a 6G system to support end to end deterministic services for industrial applications the numbering system used must be able to interoperate with the identification system of the industrial internet. This demands an architecture in which the management boundary can extend to include cross-domain and cross-layer communication systems.

Communication, sensing and computing as a converged network
Convergence of this set of capabilities will be necessary to make good use of these new capabilities, requiring a deeper integration at the architecture level including the operational management of systems to avoid adding significant complexity.

Security system based on zero trust
The transition in the telecom's industry towards security models based on zero trust architecture is a step change from existing approaches based on perimeter security. In a zero-trust architecture, no assumptions are made on trustworthiness, and secure network access is limited to users (and devices) that are authorised and approved. As cloud infrastructure is increasingly used to host enterprise infrastructure and core network features the concept of zero trust must be extended to include aspects such as the execution environment and device hardware in cloud environments. The concepts underpinning zero trust will be a key consideration in the 6G system architecture.

Simplicity and solving legacy problems
Reducing network complexity, including phasing out of legacy technologies such as 2G and 3G, provides an opportunity for future simplicity of communication networks. New features, and network functions, should adopt self-contained modules that are managed through self-organising mechanisms to significantly reduce complexity.

Disaggregation and Softwarization
Disaggregation and Softwarization (decoupling of HW and SW) of Core and RAN are either already implemented or targeted in the near future with considerable introduction efforts ongoing, for 4G and 5G. They bring flexibility for multi-vendor deployment, and flexible functional placement across the network as described in the proceeding section.

6G should be designed in a way that maintains and extends adoption of these concepts without the system integration challenges of excessive functional decomposition. To create flexibility for multi-vendor implementation, it will be important to develop the important interface specifications in relevant standardisation bodies in a timely way.

5.3 AREA CAPACITY

A significant challenge for MNOs is to economically meet the growing demand for mobile services. Projections by some regulators [4] indicate at least a x20 fold increase in traffic growth in the period to 2035 (relative to a 2021 reference), but this could be as high as x100 or x500 depending on assumptions. Further significant growth can be anticipated from 2035 if new performance-demanding services become commonly used on a wide area basis.

A proportion of this traffic growth may be accommodated through deployment of larger and more advanced antenna schemes supporting multi-layer multi-user MIMO. However, 5G is already utilising Massive MIMO antenna with a high bandwidth in 3.5 GHz spectrum, and in many lower bands, 4 or 8-layer MIMO is deployed. Antenna size and weight will constrain the extent of more advanced antenna schemes that can be supported on tower structures.

Beyond the approach of more advanced MIMO and respecting the constraint for locations that can support macro sites in urban locations, two further approaches can be considered to support mobile capacity growth: new allocations of high-power, exclusive use, IMT spectrum or small cell network densification.

Densification using small-cell networks has been explored for many years and there are different potential options including outdoor or indoor small cells, relays, repeaters, and most recently, reflective intelligent surfaces (RIS). There are technical challenges with each: spectrum may require to be dedicated which reduces the capacity of a macro-cell layer, the size and weight of equipment may be too big or heavy for installation on street assets, availability of fibre for front-haul and back-haul may constrain where sites can be located, and in-building coverage may not be achievable. Small cell networks lead to more equipment, transport, and site acquisition/rental resulting in higher capital and operational costs relative to macro cell networks delivering the same area capacity. In addition deployment of any additional hardware need to be carefully considered, as each new piece of deployed hardware may expand the CO2 footprint of the network, increasing the challenge to meeting the net-zero objectives.

The allocation of new IMT spectrum has been a more cost-effective means of extending capacity and would also be preferred from a sustainability perspective as studies [5] have highlighted that lower site densities reduce overall power consumption. This spectrum needs to be in appropriate low or mid band to provide useful coverage and capacity on a macro cell grid, although it is recognised that such resource is limited.

The 6G system design must be approached with these challenges in mind. Network Operators would need reliable sources of extra revenue coming from new services to fund the densification needed to maintain large increases in area capacity in the 6G era. Such densification therefore cannot be taken for granted today. A supply of new licenced IMT spectrum should help reduce levels of densification to make increasing area capacity more affordable, but the amounts of such spectrum in suitable bands is anticipated to be limited. Solutions that reduce the technical challenges and associated financial and energy cost of densification seem necessary to maintain area capacity growth in the long term. In parallel, alternative approaches that offload mobile data may be necessary such as self-provisioned Wi-Fi networks, dedicated private networks or hybrid private/public networks using shared access spectrum. All the above will require to be supported by 6G systems.

5.4 PEAK AND USER EXPERIENCED DATA RATES

The minimum technical performance requirement for IMT-2020 included peak rates of 20Gbps on the downlink and 10Gbps on the uplink, with target user experienced data rates of 100Mbps on the downlink and 50Mbps on the uplink. The 3GPP submission [6] to ITU fulfils the IMT-2020 requirements, however there are practical considerations which might limit the ability to reach each of these targets. In developing a 6G system, consideration must be made of practical limits.

The assumptions for IMT-2020 underpinning peak data rates assume the highest spectral efficiency on the radio link. On the downlink it is assumed that the radio link supports 8-layer transmission, and on the uplink 4-layer transmission without transmit power limit. The evaluation for peak rate is then made on the assumption that approximately 550MHz of TDD spectrum bandwidth is available.

The highest spectral efficiency using modulation format 256QAM with multi-layer transmission is only possible in specific radio conditions. The radio channel must support a very high signal to noise ratio (SNR) and the right multipath conditions for multi-layer transmission. In practice, these conditions are achieved in the absence of interference and over short radio links. This isn't a very common situation in wide area networks; therefore, the peak performance is not a meaningful metric for such deployment of 6G systems.

The targets on user experienced data rates for IMT-2020 were 100Mbps in downlink and 50Mbps in uplink. It was evaluated by multiplying an amount of spectrum with the 5th percentile user spectral efficiency, therefore considering that experienced data rate scale linearly with bandwidth. This remains true only as long as the received power remains unchanged despite the wider bandwidth, which would require either a higher transmit power or a lower path loss. Both of those options are limited by practical considerations, for example, uplink transmit power limitation or feasibility concerns of densification.

Consequences of seeking higher data rates for 6G
The achievable capacity of a radio link is given by the product of the bandwidth and the logarithm of one plus the signal to noise ratio. In practice this means that to achieve higher throughput either the bandwidth, the signal to noise ratio or the number of spatial layers must be increased. The number of spatial layers supported is limited by the number of transmit and receive antennas and characteristics of the radio channel.

The logarithmic nature of Shannon's equation means that the level of densification needed quickly becomes unmanageable at high SNR. For instance, to double the data rate starting from an SNR of 10 dB, one needs to increase the SNR to 20 dB, i.e., 10 dB path loss reduction with approximately half the cell range and four times as many sites. Scaling the available spectrum bandwidth with the data rate can avoid the logarithmic dependence on SNR. However, for a fixed radiated power, a 3 dB path loss reduction is nonetheless required leading to around 50% more sites. Consequently, for the uplink 5th percentile, even if more spectrum is made available, densification is needed to significantly increase data rates.

But densification might lead to high cost, higher overall network energy consumption and increased environmental impact. Therefore, network densification for wide area coverage will need to carefully include economical and sustainability criteria into its design to avoid an increased overall network energy consumption and environmental impact, which will happen if such a deployment is made without sufficient consideration.

For the uplink and downlink peak rates and for the downlink 5th percentile, new spectrum would help reduce levels of densification, however, it can be observed that for IMT-2020 a bandwidth of 550MHz is already necessary to achieve a peak data rate of 20Gbps. Therefore, if a scaling of x10 or x100 is sought then the bandwidths required would be in the order of 5GHz to 50GHz. Further consideration is needed to allocate these bandwidths in frequency ranges that have reasonable propagation characteristics for wide area communications and to alleviate concern on such scaling of data rates potentially becoming economically and environmentally, including in terms of energy consumption, unsustainable

For now, the following is considered. Subject to regional and national situation, if spectrum that allows a wide bandwidth allocation and has reasonable propagation characteristics is found, that spectrum would help operators to economically improve performance of wide area broadband communications. In addition, as explained in the previous section, the 6G system design should seek solutions that reduce the technical challenges and associated financial and energy cost of densification. Environmental aspects, such as energy consumption [7], must be considered at the initial release of 6G building upon the enhancements identified by 3GPP for 5G.

In this way 6G systems need to face practical limits – such as fixed radiated power and avoiding run-away energy consumption – and it is reminded that one of the essential objectives of network evolution is to improve energy efficiency and reduce absolute consumption.

To conclude, UL and DL data rate performance improvements should be sought for 6G as far as they are possible considering sustainability and economic constraints.

5.5 RELIABILITY AND LATENCY

The reliability requirement for IMT-2020[4] are stated as:

"The minimum requirement for the reliability is 1-10-5 success probability of transmitting a layer 2 PDU (protocol data unit) of 32 bytes within 1ms in channel quality of coverage edge for the Urban Macro-URLLC test environment, assuming small application data (e.g., 20 bytes application data + protocol overhead)."

The reliability and delay are sufficient for XR and the requirement is measured at the cell-edge in a wide area network. However, an additional requirement when it comes to support immersive communication is high data rates. The IMT-2020 requirement corresponds to a data rate of 32B/1ms = 256kbps whilst an immersive service requires tens of Mbps.

Further, the requirement does not include any constraint on spectral efficiency. With 5G NR it can be supported without retransmissions and using a strong code rate. To improve efficiency, e.g., to support more simultaneous users, being able to retransmit within the delay budget would be beneficial. This requires faster response times and shorter transmit cycles.

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[4] Minimum requirements related to (itu.int)

For the reliability and latency to be more relevant for immersive communications, the 6G system requirements should be complemented with a requirement on relevant data rates and efficiency.

5.6 COVERAGE

As noted in the section on "Digital inclusion", it is desirable that 6G systems deliver new services available to all. For mobile services, this implies that coverage should be sought for all areas, including rural or mountainous areas, where it can be difficult to deliver economic service with existing infrastructure solutions.

The 6G system in its design should consider how economic solutions can be developed for hard-to-reach rural areas, and this may include non-conventional solutions such as non-terrestrial high-altitude-platforms or satellite-based services to deliver mobile services.

For fully immersive communication services the 6G system should also be available in the areas in which those services are needed using the appropriate access mechanism(s).

5.7 METRICS FOR NEW CAPABILITIES

The interaction between the requirements for new capabilities such as sensing, imaging and AI/compute with communications with each other will need to be discussed qualitatively and quantitatively with, for example whether introduction of the new capabilities will require additional trade-offs to be made on the traditional communications metrics discussed in the earlier sections. The applicability of existing metrics like the coverage to the new capabilities and the new metrices that may need to be defined.
New capabilities will also need to be evaluated for their energy efficiency, which might need the definition of new metrics, their impact on overall energy consumption as well as their global environmental impact (including greenhouse gas emission, needs for new hardware and associated resources consumption).

5.8 SUMMARY OF DESIGN CONSIDERATIONS

We recommend that research, and the development of future ecosystems, should prioritise the key challenges to address societal and environmental needs, including well-being, prosperity, sustainability, security, resilience and inclusion. In addition, further enablement of digital transformation and automated industries is expected to advance, to address future market needs, with expanded and differentiated opportunities, operational efficiency, and economic sustainability.

A number of design attributes and requirements are further highlighted below:

- For most technology outcomes sought there is often a trade-off between the benefits it brings versus the costs in other aspects such as spectrum resource, spectral and energy efficiency, or environmental consequences related to the usage of finite resources. 6G systems are likely to be deployed in a period in which resource usage is under greater scrutiny when compared to previous generational changes. The outcome sought is obviously one in which end user benefits are identified at a cost which is acceptable.
  The challenge to reduce cost per bit however will remain. New approaches are needed in addition to continued efforts on simplification, energy efficiency, automation, disaggregation and softwarization. These should enable the introduction of new technology plug-ins where possible and feasible and should provide flexibility and scalability.
  To achieve sustainable, flexible deployments with simplified operations, end to end intelligent system automation, visibility / traceability, and efficient management are needed. This includes solutions to optimise network management (including the use of AI), seamless and efficient exposure of APIs, and capabilities supporting simplification, flexibility, and deployment options.
  New paradigms are needed to address traffic growth, extreme requirements (such as immersive, critical, massive, native), capacity needs, minimisation of added complexity, and the alternatives to densification (such as multi-access and offload, novel complementary solutions, dedicated private/public networks, data relevance and efficiency, new spectrum, and shared networks), given the practical limits of wide-area mobile systems and the critical goal of reducing overall network energy consumption.

- As previously indicated, the trends point to a few classes of potential use cases and new enabling paradigms. The capabilities related to these enablers will likely develop and mature at different rates, therefore specific use cases may need a phased evolution.

  Service versatility must be provided where and when applicable and relevant as all capabilities may not be concurrent or provided simultaneously. There will be flexibility to make trade-offs for deployment so that use cases with extreme requirements are enabled where and when needed. Some services may experience co-existence or potential concurrence for resources (e.g. communication, computing, sensing and AI). This should be enabled by efficient optimisation of resources and interactions, in addition to privacy, data protection, local-offload trade-offs, power constraints and energy efficiency.

  Design considerations and imperatives ensure the goals and motivations of 6G are met with societal, environmental, and economic sustainability, enabling superior user experience, performance, and capabilities, advancing digital transformation with new and differentiated services, and opening new market opportunities.

06 CONCLUSIONS AND FUTURE WORK

The 6G system is expected to be built upon the features and capabilities introduced with 5G, alongside new capabilities, to deliver new services and value. Any new technology should enable superior functionalities and capabilities, supporting new and differentiated services, advancing digital transformation and opening new market opportunities, considering efficiency and affordability. Sustainability that includes energy efficiency and adoption of green technologies and green energy, towards carbon neutrality, is a key focus of NGMN, for this decade and beyond and should be a fundamental design consideration for 6G.

This 6G publication is intended to provide guidance on the identified trends related to use cases, as well as highlighting essential needs in network evolution.

The essential needs are particularly directed towards building networks that deliver digital inclusion, that are environmentally and economically sustainable, that reduce complexity, address traffic growth and enable new services through additional features that are complementary to existing mobile networks.

At this stage, there is no decision on whether a new radio access technology or core network is required for mobile services. However, the views of NGMN indicate that for a fundamental change to take place there must be significant benefits in essential metrics such as spectrum and energy efficiency that justify the cost and complexity in technology migration. In any migration to 6G the transition should be carefully considered to ensure that 5G networks are not compromised with regards to spectral efficiency, and that the features provided by 6G provide end-user value through the addition of new features or the ability to reduce operational cost and subsequently improve affordability.

As 6G research continues through international collaboration, the understanding of potential improvements in spectrum and energy efficiency will become clearer. In parallel, 5G deployment using 5G SA, product evolution and optimisation, distributed cloud and intelligence, and new capabilities such as edge computing and dynamic service provision, will become more established and set for where market demand exists for new services. This combination of 5G forward-looking features and market demand and the capabilities identified from 6G research are then expected to converge with clear outcomes and recommendations for future network deployment.

A healthy global ecosystem, including interdisciplinary research and innovations, and global standardisation, will be essential to a successful introduction addressing the drivers of 6G and the design requirements providing a graceful path.

07 ABBREVIATIONS

3GPP	3rd Generation Partnership Project
5G	The fifth generation of mobile system standard
5G-NR	5G New Radio
5G SA	5G Stand Alone
5GC	5G Core network
5G SBA	5G Service Based Architecture
6G	The sixth generation of mobile system standard
6G-RAT	6G Radio Access Technology
AI	Artificial Intelligence
AIaaS	Artificial Intelligence as a Service
CU	Centralised Units
DU	Distributed Units
ESG	Environmental, Sustainability and Governance performance
IETF	Internet Engineering Task Force
IMT	International Mobile Telecommunications
IMT-2020	Requirements issued by the ITU-R for 5G networks
IMT-2030	Requirements issued by the ITU-R for 6G networks
IMT-R	IMT Radiocommunications Sector
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunications Sector
MIMO	Multiple-Input Multiple-Output
NIST	National Institute of Standards and Technology
NGMN	Next Generation Mobile Network Alliance
NW	Network
O_RAN	Open Radio Access Network
PDU	Protocol Data Unit
PLMN	Public Land Mobile Network
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RIS	Reconfigurable Intelligent Surfaces
SDO	Standard Development Organisation
SNR	Signal to Noise Ratio
TDD	Time-Division Duplexing
XR	eXtended Reality

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NEXT GENERATION MOBILE NETWORKS ALLIANCE e.V

NGMN, established in 2006, is a global, operator-led alliance of over 80 companies and organisation spanning operators, manufacturers, consultancies and academia.

VISION

The vision of the NGMN Alliance is to provide impactful guidance to achieve innovative and affordable mobile telecommunication services for the end user with a particular focus on supporting 5G's full implementation, Mastering the Route to Disaggregation, Sustainability and Green Networks, as well as 6G.

MISSION

The mission of the NGMN Alliance is

- To evaluate and drive technology evolution towards 5G's full implementation and the three major priorities for 2021 and beyond:

  Route to Disaggregation: Leading in the development of open, disaggregated, virtualised and cloud native solutions with a focus on the end to end operating model.

  Green Future Networks: Building sustainable and environmentally conscious solutions.

  6G: Emergence of 6G highlighting key trends across technology and societal requirements plus use cases to address.

- to establish clear functional and non-functional requirements for mobile networks of the next generation.

- to provide guidance to equipment developers, standardisation bodies and cooperation partners, leading to the implementation of a cost-effective network evolution

- to provide an information exchange forum for the industry on critical and immediate concerns and to share experiences and lessons learnt for addressing technology challenges

- to identify and remove barriers for enabling successful implementations of attractive mobile services