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ICT - Information and Communication Technologies

Deliverable D2.4
Second technology roadmap for advanced wireless

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Executive Summary

This deliverable presents the second technology roadmap developed within the EMPOWER project. It builds on top of the first technology roadmap presented in D2.2 [1] and referenced in the Horizon Europe SNS Partnership Proposal [2] and on the update on technology trends included in D2.3 [3]. The following list summarizes the key achievements in this deliverable compared to the baseline roadmap in D2.2 [1]:

- Update of the target capabilities for future wireless (a.k.a. IMT-2030)
- Addition of target capabilities for future network (a.k.a. NET-2030)
- Update of the technology roadmap for future wireless (IMT-2030)
- Addition of a technology roadmap for future network (NET-2030)

This deliverable should be read in conjunction with the baseline roadmap in D2.2 [1], as it focuses on updates to D2.2 [1] therefore avoiding duplication as recommended by the reviewers at the first periodic review.

Acronyms

3GPP	Third Generation Partnership Project
5G NR	5G New Radio
5GAA	5G Automotive Association
5G-ACIA	5G Alliance for Connected Industries and Automation
5G-PPP	5G Infrastructure Public Private Partnership
AaaS	Analytics-as-a-Service
AI	Artificial Intelligence
AIICT	Artificial Intelligence Information and Communication Technologies
API	Application Programming Interface
AR	Augmented Reality
ATIS	Alliance for Telecommunications Industry Solutions
B5G/6G:	Beyond 5G and 6G
CTM	Critical Path Method
DoF	Depth of Field
EMF	Electromagnetic Field
EMPOWER	Empowering translatlantic PlatfOrms for advanced WirEless Research
ETSI	European Telecommunications Standards Institute
FEC	Forward Error Correction
FPS	Frames per second
Gbps	Gigabytes per second
GEO	Geo-stationary Orbit
GSMA	Global System for Mobile Communications
HAP	High-Altitude Platform
HDR	High Dynamic Range
ICTAI	Information and Communication Technologies Artificial intelligence
IEEE	Institute of Electrical and Electronics Engineers
IMS IP	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
ITU-R	International telecommunication Union. Radiocommunication Sector
JCS	Joint Communication and Sensing
KPI	Key Performance Indicator
LAN	Local Area Network
LDPC	Low Density Parity Check
MAC	Medium Access Control
Mbps	Megabits per second
MDT	Minimization of Drive Test
MEC	Multi Access Edge Computing
MEMS	Microelectromechanical system
MIMO	Multiple Input Multiple Output
ML	Machine Learning
MNO	Mobile Network Operator
MR	Mixed Reality
NET 2030	Network 2030
NFV	Network Functions Virtualization
NGI	Next Generation Internet
NGMN	Next Generation Mobile Networks
NOMA	Non-Orthogonal Multiple Access
NSF	National Science Foundation
NTN	Non-Terrestrial Networks
OAM	Operations, Administration and Maintenance
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operational Expenditures

O-RAN	Open Radio Access Network
PHY layer	Physical layer
PloT	Personal Internet of Things
RAN	Radio Access Network
RRM	Radio Resource Management
SNS	Smart Networks and Services
SON	Self-Organising Networks
TCO	Total Cost of Ownership
TRX	Transceiver (Transmitter and Receiver)
TX tech	Texas Tech University
UAS	Unmanned Aircraft System
UL/DL	Uplink/Downlink
VLEO system	Very Low Earth Orbit
VR	Virtual Reality
WIPT	Wireless information Power Transfer
WIT	Wireless Information Transfer
WLAN	Wireless LAN
WP5D	Working Party 5G
WUR	Wake-up Radio
WUS	Wake-up System
XaaS	Anything as a Service
xEO	X Earth Orbit
XR	Extreme Reality

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1. Introduction

The year 2020 witnessed a significant momentum around 6G visions and roadmaps from all stakeholders including the Academia, the Industry and Governments. On the academic research front, a simple search on IEEE Xplore (https://ieeexplore.ieee.org/Xplore/home.jsp) for IEEE peer-reviewed publications including the keyword 6G shows a striking 7-fold increase in 2020 compared to the year 2019.

Similarly, on the Industry Front, several whitepapers have been published by key players outlining 6G visions and roadmaps, and importantly, key International Forums such as ITU-R WP5D [4] and NGMN [5], have already started formal activities to progress towards global consensus around 6G in what is now called as IMT-2030 vision.

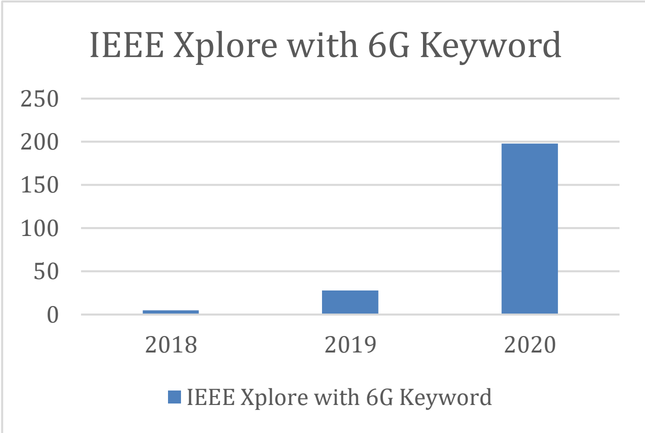

Figure 1 – Chart showing the increase in IEEE. publications on 6G.

Government agencies such as the European Commission in Europe, NSF and ATIS in the USA, and similar agencies in Japan MIST, South Korea 6G Forum, and China Future Forum, have all been busy laying out their multi-year multi-billion national research programmes on 5G evolution and 6G. Another example of this trend can be seen on the 5G-Office of Taiwan, which has been recently renamed as the 6G Office.

In addition, research programmes looking at setting the basis for 6G development have started to appear in all geographical areas. Specifically, in the European Union, pre-6G projects such as Hexa-X (ICT-52 call system/flagship) [6] are starting the development of use cases, KPIs analysis and target technologies. At the USA side, ATIS has recently launched the Next G Alliance, agglutinating well-known companies such as Qualcomm, Ericsson, Nokia, InterDigital, Apple, Google or Samsung in joint research efforts towards 6G.

Amidst this fury on 6G roadmaps throughout 2020, the EMPOWER consortium has been actively disseminating its first baseline roadmap developed in 2019, while refining this roadmap to best capture the progress made in identifying the emerging use cases, requirements and capabilities, and technology trends for both future wireless and future networks.

This report comes to summarize the EMPOWER efforts in refining and updating the technology roadmap. Following the seven steps methodology for the identification of technology gaps and trends developed in D2.2, this deliverable updates the baseline roadmap as follows. Chapter 2 provides first an update on the target capabilities for future wireless (IMT-2030) and extends the work by adding target capabilities for future network (NET-2030). This is next followed in Chapter 3 with an update on the technology trends for meeting the forecasted target capabilities of both IMT-2030 and NET-2030. Finally, Chapter 4 draws the conclusions and outlines the next steps.

2. Update on Target Capabilities

2.1 Use Cases and Requirements

2.1.1 Short-Term and Medium-Term Evolution

In the short to medium terms evolution of 5G, several use cases and their corresponding requirements have already been the subject of study and specification in the 3GPP Release 17 and Release 18 SA1 Technical Specification TS 22.261 [7] and TS22.104 [8]. The non-exhaustive list below outlines key 3GPP Release 17 and Release 18 studies for services and characteristics driving new requirements into the 3GPP evolution of 5G:

- TR 22.821: Feasibility Study on LAN Support in 5G
- TR 22.832: Study on enhancements for cyber-physical control applications in vertical domains
- TR 22.839: Study on vehicle-mounted relays
- TR 22.844: Study on 5G Networks Providing Access to Localized Services
- TR 22.847: Study on supporting tactile and multi-modality communication services
- TR 22.855: Study on ranging-based services
- TR 22.858: Study on enhancements for residential 5G
- TR 22.859: Study on Personal Internet of Things (PIoT) networks
- TR 22.867: Study on 5G smart energy and infrastructure
- TR 22.873: Study on evolution of the IP Multimedia Subsystem (IMS) multimedia telephony service
- TR 22.874: Study on traffic characteristics and performance requirements for AI/ML model transfer
- TR 22.878: Study on 5G timing resiliency system
- TR 22.989: Study on Future Railway Mobile Communication System
- TR 22.990: Study on off-network for rail

From the above studies, one can identify the following service categories as key drivers for the evolution of the 5G KPIs in the short-medium terms [9]:

- Extreme Reality (XR)
- Smart Industries
- Private, Personal and Local networks
- Future Railways
- Unmanned Aerial Vehicles (UAV)
- Non-terrestrial satellite services
- Massive IoT (tens of millions of UEs)
- Advanced V2X services

These services come with various combinations of requirements such as user experienced data rates, latency, reliability, positioning (horizontal and vertical) accuracy, coverage, connections density, range and mobility. They also introduce a need for significant improvements in resource efficiency in all system components (e.g., UEs, IoT devices, radio, access network, core network).

2.1.2 Long-Term Evolution

Several use cases have also been emerging to drive requirements for long-term evolution of 5G. These use cases are not particularly new, but they present roadmap of requirements to be ultimately met towards the end of the decade through what is dubbed as 6G. The four categories below embody the key use cases driving new requirements for 6G [9][10]:

- Multi-Sensory Extreme Reality (XR) and Haptics
- Connected Industries and Automation
- Autonomous Vehicles and Swarm Systems
- Extreme Coverage and Reaching the last Billion

Multi-sensory extended reality (XR) and haptics describe the wide category of real-world to virtual-world interactions between humans and machines. It encompasses VR, AR and MR and everything in between. XR is already transforming consumer experiences and many market verticals, from manufacturing and healthcare to education, gaming and retail. But this category is still in very early stages and has a long way to run. XR challenges are immense and incremental breakthroughs will lead to progressive product entries. Wireless has a critical enabling role but todays minimum target 5G User Data Rate as per ITU-R IMT-2020 requirements (100 Mbps in downlink and 50 Mbps in uplink) will barely meet entry needs especially as advanced immersive experiences such as with next-generation 360 degrees video (8k, 9FPS, HDR, stereoscopic) and 6 DoF videos call for user data rates up to 5000 Mbps (5Gbps) [11]. In addition to user data rate, as this new category grows and applications expand, stringent requirements on Energy Efficiency, Connection Density and Latency will also be pushed.

Connected Industries and Automation (a.k.a. Industry 4.0 – I4.0) describes a wide category of industrial IoT use cases and it has become apparent that only a subset are addressable by current 5G KPIs. This includes advanced applications in manufacturing, logistics, oil and gas, etc. Wireless promises transformative productivity, flexibility, speed & efficiency improvements. B5G/6G still has much work to do in Industrial space. Private networking in industrial applications remains one of the biggest growth areas for wireless communications. Through organized forums like the 5G-ACIA, new requirements are emerging that 5G will struggle to satisfy [12]. Wireless will need to rise to fiber-like performance not only in speed but in latency, reliability and availability. Positioning accuracy (cm-level) is also emerging as a critical new requirements especially in robotics control.

Autonomous Vehicles & Swarm Systems describes a wide category of swarms of drones, robots & transport which hold enormous promises in increased productivity and efficiency when enabled at scale. Applications are forecast in transportation, monitoring, surveying & mapping, precision agriculture, etc. and what we see today is just the start of trend that will place high demands on wireless. Autonomous swarms describe a suite of use cases with a range of KPIs only a subset of which are scoped in 5G today. Clear new requirements are emerging through forums like the 5GAA & NGMN provided by vertical players [5][13]. Wireless will need to evolve in response to this roadmap with KPI improvements in Latency & Positioning accuracy. Reliability will also be increasingly important and will push 5G system beyond its target KPI today.

Extreme Coverage & Reaching the Last Billion describes the wide category of remote coverage use cases which have been a challenge in every wireless generation but in B5G/6G this challenge will expand to include a broader non-terrestrial dimension (e.g., HAPs, Satellites, etc.) deployed at scale. Integration of these new "nodes" will be a challenge but may also be the solution to covering the last billion. Non- Terrestrial Networks (NTN) integration has many dimensions and will take years. There have been many false starts with NTN integration but 3GPP recent embrace suggests a new beginning. This may herald the start of a new era of convergence akin to but an order of magnitude higher than Cellular-WiFi. Many of the challenges will be system integration but the measure of KPI success will be Coverage Area Probability. Within this new expanded seamless system vision, all other KPI (User Data Rate, Latency) are also likely to challenge today's 5G performances.

The impact of the above extreme use cases on some of the current 5G NR KPIs is captured in the heat map illustrated in Figure 2 below [10]. A red color means high impact, orange means medium impact, and green means low impact in terms of the level of enhancement required on today's 5G KPIs.

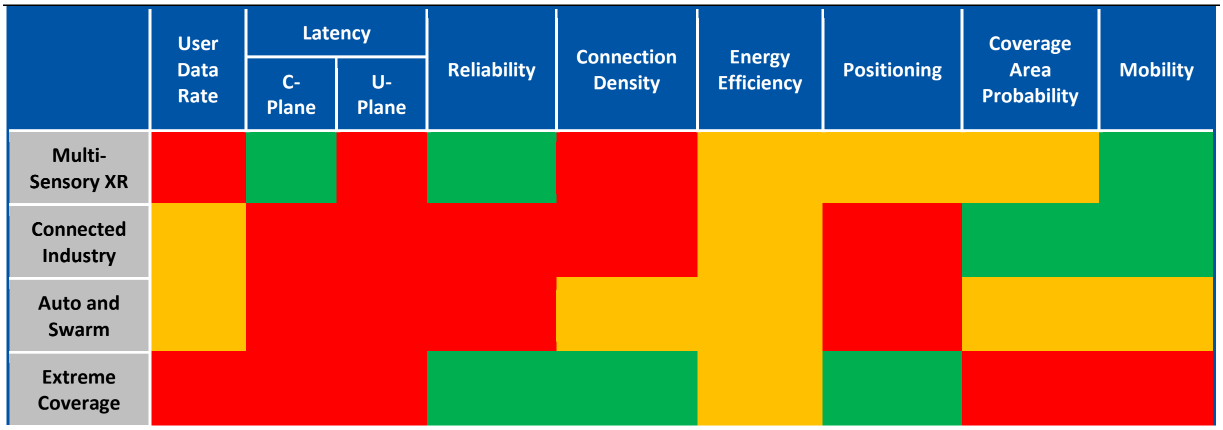

Figure 2 – Heatmap impact of emerging use cases on 5G KPIs.

2.2 Target Performance Capabilities

The performance capabilities of today's 5G are already evolving to accommodate new requirements from the various service categories and markets. The evolution of these capabilities is incremental and will only make leap enhancements when backward compatibility with 5G is relaxed to start developing 6G. In the figures below, we show the directions of travel of the performance capabilities from today's 5G in 2020 towards 6G by 2030.

On the wireless interface side, we take as a reference IMT-2020 radio interface capabilities and project them into forecasted capabilities for the IMT-2030 radio interface capabilities. This is shown in Figure 3 below.

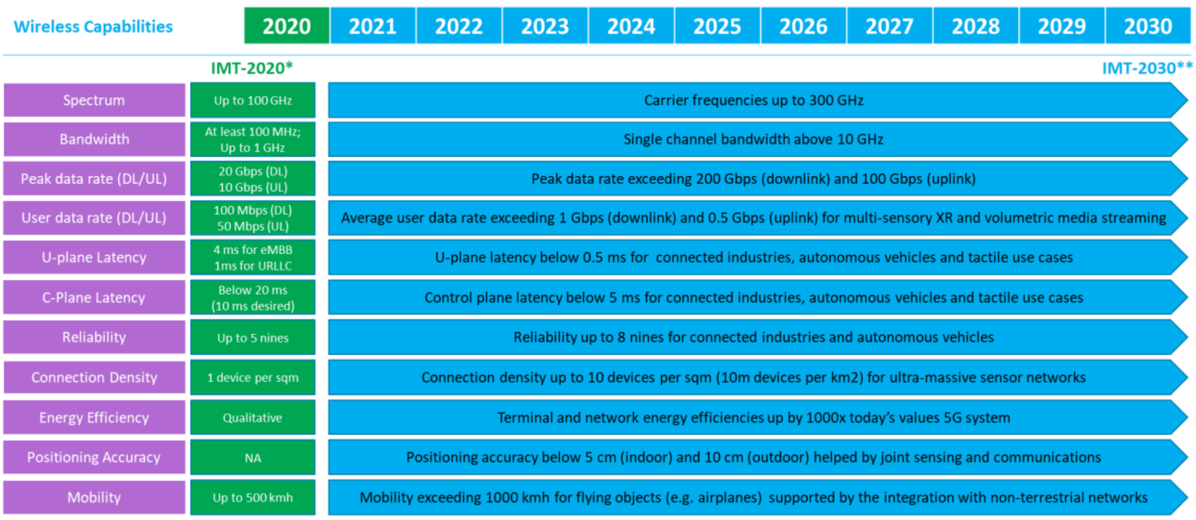

Figure 3 – Radio Interface Capabilities from IMT-2020 to IMT-2030.

Summarizing the above information, we can expect an order of magnitude increase in the requirements of the following metrics:

- Bandwidth: From up to 1 GHz in IMT-2020 to up to 10 GHz in IMT-2030.
- Peak data rate: From 20/10 Gbps (DL/UL) in IMT-2020 to 200/100 Gbps (DL/UL) in IMT-2030.
- User Data rate: From 100/50 Mbps (D/UL) in IMT-2020 to 1/0.5 Gbps (DL/UL) in IMT-2030.

This increase in the bandwidth and rates is supported by an increase in the spectrum usage increasing up to 300 GHz (from 100GHz baseline) in IMT-2030.

Regarding latency, it is expected to continue the trend on ultra-low latency communications, reaching the barrier of U-Plane delay of 0.5 ms for mission critical and tactile use cases in IMT-2030, and a C-Plane delay of barely

5ms. Reliability will follow a similar trend, with some services requiring up to 8 nines reliability figures in IMT-2030. While the rest of KPIs (connection density, position accuracy and mobility) follow a similar trend, it is worth considering the Energy Efficiency of the network. Improvements in IMT-2030 both in terminal and network energy efficiencies are expected to up by 1000 times today's values in in IMT-2020

On the network side, in the absence of an equivalent of an international organization like ITU-R for network 2020, we take multiple references on 5G network capabilities from organizations such as NGMN, GSMA, and 5G-IA 5G-PPP, and project these into forecasted capabilities for the Network 2030 capabilities based on forecasts available from forums such as ITU-T NET2030 focus group and Horizon Europe SNS Partnership. This is shown in Figure 4 below.

Network Capabilities	2020	2021 – 2030
	NET-2020	NET-2030*
Automation	Human operated	Self-operating requiring human operators to only validate the decisions
Flexibility	Service-based and slicing limited to core/transport	Fine-grain flexibility based on micro-services and improved end-to-end slicing (core; transport; access; device)
Service deployment time	Few hours	Reduced by a factor of 10 compared to similar tasks in 2020, based on slice creation and instantiation on the fly
Latency	Few tens of ms	Enabling application to application response time in the few milliseconds range
Determinism and Resilience	Limited to wired	Extended to support deterministic and resilient networking for industrial wireless
High network bandwidth	100s Gbps and a few biillion devices	Supporting Terabits per second throughputs and trillions of devices
Data-driven and distribution	Centralized big-data based analytics in core and cloud	Supporting small-data based distributed analytics and distributed AI
Energy consumption	Moderate	A significant energy reduction of network operation compared to 2020
EMF-awareness	Moderate	Support deployment in areas with challenging EMF limits (due to spectrum bands and network densification)
Coverage	Segregated terrestrial and satellite	Ubiquitous based on integration of terrestrial and non-terrestrial networks (satellites and HAPs)
Security and trust	Moderate	Enhanced security based on cyber-physical integration; AI; and quantum keys

Figure 4 – Network Capabilities from NET-2020 to NET-2030.

Summarizing the above information, we can expect significant enhancements in the following key network capabilities:

- Automation: From human-operated networks in 2020 to self-operating network in 2030 requiring human operators to only validate certain decisions.
- Service deployment time: Reduction by a factor of 10 supported by enhancements of network slice creation, instantiation, and scaling.
- Latency: Reduction by a factor of 10 from few tens of ms today to few ms at the application level in support for further mission critical and tactile applications.
- Data-driven and distribution: From centralized big data-based solutions to distributed small-data based analytics and artificial intelligence.
- Energy consumption: Move to green network with significant reduction in network energy footprint compared to today.
- Coverage: Move to a ubiquitous coverage based on full integration between terrestrial and non-terrestrial networks.
- Security and Trust: Enhancements based on cyber-physical integration, use of AI and quantum keys distribution.

3. Update on Technology Trends

This chapter provides an update on the wireless and network technology trends for the short, medium, and long terms evolution of 5G. These are positioned as enabling technologies to meet in the long term the target capabilities outlined in previous Chapter 2.

3.1 Wireless Technologies

Figure 5 presents a 10-years roadmap depicting the evolution of key wireless technologies in the short, medium, and long terms from 2020 to 2030. For each technology, a reference of the current (2020) state of the art is presented in green background. The technologies listed in the roadmap below contribute to meeting the long-term target wireless capabilities presented in Chapter 2.

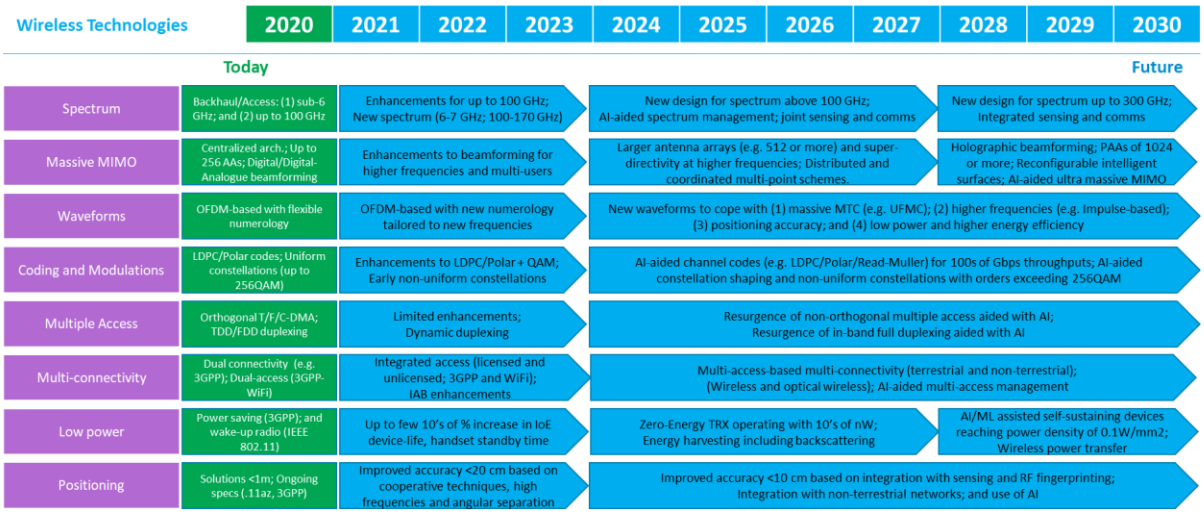

Figure 5 – Wireless Technologies Roadmap.

Below we have shortlisted four wireless technologies for further discussion:

- Push into Higher Frequencies
- Reconfigurable Intelligent Meta-surfaces
- Convergence of Communications, Imaging & Positioning
- Spectral Efficiency to Energy Efficiency

3.1.1 Push into Higher Frequencies

Moving into higher frequency bands is a certain trend for achieving average user data rates >1Gbps. This will require: 1) Novel compact modules to compensate for more severe path-loss and absorption, and high-complexity digital processing due to much higher-bandwidths; and 2) New link and medium-access level technologies designed to cope with energy constraints and ultra-directive short-range beams. New technologies may include device and RF-aware new waveforms, low complexity encoder/decoder designs, and efficient ultra-massive MIMO techniques. The short-, medium- and long-term roadmap is summarized in Table 1.

Table 1 – Short, medium and long -term roadmap in the evolution of 5G towards higher frequencies.

Short Term	Medium Term	Long Term
72GHz-100GHz: Mature precommercial TX tech. with applications in NGI, XR & JCS. Throughputs in excess of 50Gbps forecast.	**Above 100GHz:** Lab grade reference designs & testbeds. Future applications in NGI, XR & JCS. Throughputs in excess of 100Gbps.	**Up to 300GHz:** Still mostly academic with experimental TX designs & testbeds. Throughputs up to 1000Gbps.

3.1.2 Reconfigurable Intelligent Meta-surfaces

The incorporation of large antenna surfaces capable of steering radio waves in a controlled manner (i.e., enabling control of channel characteristics) is emerging as a promising area. This large-scale bending of Snell's Law may be a key to achieving new coverage KPI and other breakthroughs. The progression of this trend will challenge basic system design paradigms and will progressively impact the evolution of technologies and protocols in both infrastructure and access. The meta structure core technology is maturing and opening the door to necessary system level and new capability innovation in years ahead. Beyond pure communications, applications in PHY layer security, wireless power transfer and positioning are forecast. Worth highlighting IEEE 802.11bf, wireless sensing is also studying meta-surfaces as enhancements to enhance the sensing characteristics of WLAN in the 60GHz spectrum. The short-, medium- and long-term roadmap is summarized in Table 2.

Table 2 – Short, medium and long -term roadmap of reconfigurable intelligent surfaces towards 6G.

Short Term	Medium Term	Long Term
In the nearer term opportunity lies in the areas of coverage, directivity and range extension in support of massive MIMO and new band applications up to 50GHz	Expands to support of multi-Gbps links and applications in outdoor and indoor positioning (high resolution localization). Support in bands up to 100GHz	Support of data rates >100Gbps@1000GHz frequencies, holographic MIMO (1000's of elements), wireless power transfer below 1GHz and new PHY layer security methods

3.1.3 Convergence of Communications, Imaging & Positioning

Sixth sense uses cases such as gesture recognition, presence detection, "see through" vision will only be possible through advances in joint communications and sensing. Progress on this trend line will be key for positioning accuracy and control-loop latency KPI objectives. More, technology breakthroughs that enable joint capabilities may bring lower complexity and lower costs. PoCs and more mature developments have proven the feasibility of this convergence, but to date capabilities have been limited and much more innovation is required. A full and seamless integration of sensing and imaging capability in the wireless communications (PHY layer) will require new waveform design that will not be supported by progressive upgrades to current 5G design. In time, a new PHY design to support broader service set, need communications and control co-design will impact all layers of the protocol stack, and will provide one of the key enablers for many of the target 6G use cases (e.g., XR). The short-, medium- and long-term roadmap is summarized in Table 3.

Table 3 – Short, medium and long -term roadmap of joint communication and sensing towards 6G.

Short Term	Medium Term	Long Term
Many proprietary solutions focused on single use cases e.g., gait recognition, fall detection,	Mature Standards for joint communication and Sensing, sensor fusion integrated into the	Full support of sensing, communications, imaging and positioning in integrated PHY

etc. Beginning of standards efforts in the study item phase (e.g., IEEE 802.11bf)	wireless framework, emergence of first sensing and communication chipsets	design, communications & control co-design, new end user device types with various shapes and form factors

3.1.4 From Spectral Efficiency to Energy Efficiency

Today, spectral efficiency system design paradigm is not sustainable under the longer-term evolution of 5G KPI and the anticipated explosion of device form factors. Reduction in modem energy consumption and power density by up to 100x will be necessary to support 6G user data rates. Scaling to 100's billions of IoE and novel UE device types will require a paradigm shift from wireless information transfer (WIT) to wireless information and power transfer (WIPT) on a universal scale. Power generation "out of thin air" in devices is becoming a reality thanks to advances in energy harvesting, MEMS and antenna technology but much more will be required such as: 1) Novel energy-aware air interface design (waveforms, modulation, FEC & MAC) driving to 1pJ/bit consumption; and 2) AI driven dynamically reconfigurable radio elements leveraging multi-band, multi-RAT and meta-material antenna tech balancing ever conflicting KPIs, Energy vs. user data rate, latency, reliability, etc. The shift from WIT to WIPT for devices will require a redesign of fundamental blocks in air-interface design such as radio aware waveforms, modulation techniques such as CPM and impulse radio, low complexity encoder/decoder designs, and efficient multi-connectivity techniques. The short-, medium- and long-term roadmap is summarized in Table 4.

Table 4 – Short, medium and long -term roadmap of energy efficiency towards 6G.

Short Term	Medium Term	Long Term
Wake-Up Signal (WUS)/Wake-Up Radio (WUR): Maturing technology with implications across IoT, handsets & wearables. Up to few 10's of % increase in IoE device-life, handset standby time.	Zero-Energy Air-interfaces, FEC exceeding 100 Gb/s: Lab grade reference designs & testbeds. Zero-Energy TRX operating with 10's of nW; Forward Error Correction (FEC) throughput exceeding 100's of Gb/s.	AI/ML assisted self-sustaining devices reaching Tb/s processing capabilities: Still mostly academic with few design proposals for full charge-free operations. Focus of reaching 1pJ/bit with power density of 0.1W/mm2.

3.2 Network Technologies

Figure 6 presents a 10-years roadmap depicting the evolution of key network technologies in the short, medium, and long terms from 2020 to 2030. For each technology, a reference of the current (2020) state of the art is presented in green background. The technologies listed in the roadmap below contribute to meeting the long-term target network capabilities presented in Chapter 2.

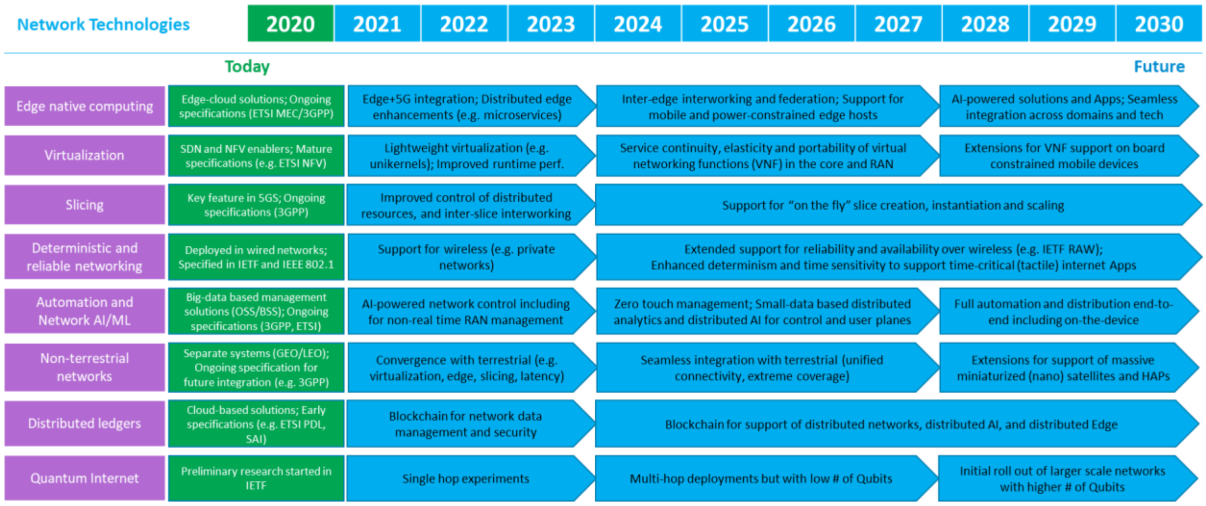

Figure 6 – Network Technologies Roadmap.

Below we have shortlisted four network technologies for further discussion:

- Fusion of Wireless and Networking with AI/ML
- Convergence of Terrestrial and Non-Terrestrial networks
- Virtualization to Cloud Native Computing
- Towards Ubiquitous Edge Native Computing

3.2.1 Fusion of Wireless and Networking with AI/ML

Wireless and AI/ML fusion is already happening. The question is perhaps more just where will AI/ML NOT play in future? AI/ML is used in wireless today but is limited to Applications, SON/RRM/MDT and Core Network OAM. B5G/6G challenges include many hard to model non-linear optimization problems which are ideal for AI/ML. Today, most AI/ML applications rely on centralized high compute, cloud based, and big data systems. For fusion to progress, this approach will need to refine and evolve to move away from proprietary data models and often complex and energy consuming AI/ML solutions towards open/standardizable lower complexity/lower energy AI/ML solutions. Intuitively, making nodes progressively more intelligent than they have ever been before will have an impact on future radio and network interfaces design perhaps to a point that will challenge traditional principles (e.g., AI/ML based solutions may replace conventional model-based Layer 1 design as we move towards 6G). The end of traditional protocol design may result in a transition from hand crafted specialized protocol solutions to black box ML solution. This has also the potential of moving from long-time cycle standardization to short cycle ML model and training-based standardization. The short-, medium- and long-term roadmap is summarized in Table 5.

Table 5 – Short, medium and long -term roadmap of Wireless AI fusion towards 6G.

Short Term	Medium Term	Long Term
Exploring every permutation but lead industrial research area continues in Core and Edge Network orchestration and optimization, and RAN SON/RRM/MDT	Enabled by standards development, AI/ML will use small data and migrate towards the middle layers of the stack. Support for near-real time emerging.	Massive small data-based AI/ML embedded in All protocol stack Layers and All network nodes. Fully distributed AI with lifelong learning.

3.2.2 *Convergence of Terrestrial and Non-Terrestrial networks*

After many false starts in earlier generations, terrestrial and non-terrestrial networks (including UAS, HAP and xEO) integration is finally happening introducing a new dimension with a long evolution path. Satellite industry players are actively engaged in 3GPP with motivation and know-how to push forward this integration. Lower cost per bit argument too: Study suggests a 1.18Pbps VLEO system is 45x cheaper than terrestrial [15]. 3GPP has been studying this area and its application to both infrastructure and access since Release 15. Formal standards work has begun in Release 17 but has a very long way to go. Big challenges created by long propagation delay, large doppler effects, moving cells, different architecture and NTN permutations still need solutions. VLEO seems to be the key enabler but is not without risk. Extreme coverage, service continuity and availability KPIs coupled with improving NTN technology economics will be driving this convergence in both infrastructure and devices. NTN may fulfil the 5G/B5G promise to cover the "last billion", but while there remain core technology challenges architectural hooks will likely be put in place in B5G that will be built on further in 6G. The short-, medium- and long-term roadmap is summarized in Table 6.

Table 6 – Short, medium and long -term roadmap of non-terrestrial networks towards 6G.

Short Term	Medium Term	Long Term
3GPP NTN work (on 3 architecture options) continues through R17/18 and beyond with focus on LEO-600/1200, GEO and UAS (inc. HAPS)	Focus turns to VLEO systems to address new challenges created: Higher Doppler, address time/frequency Higher Doppler, Synchronization, Uniform addressing, routing, admission control, Virtualization and Edge Computing Impacts	Extensions to support massive miniaturized (e.g. nano) satellites and high altitude platforms (HAPS).

3.2.3 *From virtualization to Cloud Native Computing*

3GPP Core Network and ETSI MEC are both built on the same ETSI NFV reference architecture that has finally embraced a full Cloud Native model approach. Migration to full cloud-edge native will be critical in meeting future business and technical KPIs (e.g., Latency and Energy). Progression on this roadmap will present technical, business, regulatory and IPR challenges beyond 5G. Whilst 5G is well on track to cloud-edge native in Core and Edge, this journey has only just begun in the RAN through initiatives like O-RAN, and much more is needed and possible. In the core network, the progress has stalled in control plane functions, in face of reluctance from *hostile* established vendors, whereas in the RAN, Virtualized RAN is "Holy Grail" with huge technical challenges in opening vendor interfaces. Increasing challenges to reduce TCO/OPEX and to find new revenue opportunities will continue to drive the core network and RAN roadmaps forward on a convergent path for cloud native virtualization. The short-, medium- and long-term roadmap is summarized in Table 7.

Table 7 – Short, medium and long -term roadmap of Cloud-native networking towards 6G.

Short Term	Medium Term	Long Term
Continued enhancements in the core and edge to support ever tighter integration and increasing opening of Network Functions to 3rd Party players RAN level slicing, Network exposure & Analytics	Evolution to a pervasive distributed open edge with Network Functions beginning to look more like application services, with increasing blurring of the lines between Public & Telco/Edge clouds	Extreme Cloud-Edge convergence to a huge, distributed computing fabric, consuming Core, RAN & Device, progressive decomposition of Network functions into a new on-demand, orchestrated, AI/ML enabled, Algorithm-as-as-Service model.

3.2.4 Towards Ubiquitous Edge Native Computing

Edge computing today is primarily limited to content distribution in operator infrastructure, but much innovation is needed to enable edge servers across B5G/6G devices. Use cases like autonomous vehicles, swarming robots, industrial IoT will require local compute, real time decisions and stack response time latencies in the order of sub-millisecond levels. New coordination methods across edge-cloud stack domains will be needed while balancing strict latency KPI. Future connectivity choices will be based on joint network and compute resource decisions, driven to support KPI goals in Latency and User Data Rate. The low end-to-end latency needs of 5G/6G applications will not be achievable by the access network alone. New service engines (AI, sensing, localization) will need to be integrated across the mobile network with control open to app developers. Like virtualization, these changes will push on industry boundaries and relationships. As a result, this may not happen until we turn page to 6G. The short-, medium- and long-term roadmap is summarized in Table 8.

Table 8 – Short, medium and long -term roadmap of Edge networking towards 6G.

Short Term	Medium Term	Long Term
Exploiting techniques from the cloud (e.g., microservices, serverless, etc.) to establish the foundation for Edge-Enhanced applications at MNO edge centers	1) Extension to mobile addressable edge resources (e.g., compute, GPU, etc.) at premise and terminal device edge 2) Inter-edge interfaces, enabling edge resource migration across providers	Ubiquitous Edge Native Application Architectures operating seamlessly across multi-access networks and domains (cloud / telco edge / device edge)

4. Conclusions and Next Steps

This deliverable presented an update of the EMPOWER baseline roadmap for the evolution of 5G in the short, medium, and long terms towards 6G.

Since the first EMPOWER technology roadmap, D2.2, was published in October 2019, followed by a public consultation, the attention to 6G has increased significantly, as shown in the introduction (chapter 1). The number of research publications have multiplied, as well as the focus from the standards and industry communities. Government agencies in Europe, the US, and in Asia are defining and kick-starting large research programmes with the aim of developing the essential technologies and visions for B5G and 6G.

To update the target capabilities, we have identified some essential drivers for new use cases in chapter 2, like extreme reality (XR), smart industries and massive IoT, which are all pushed for in the short- and medium-term evolution perspective. We have also identified a few studies being done by 3GPP pointing forward to Release 17 and beyond. In the long-term perspective we have identified four categories of use cases, which we believe will be key drivers for the technology push towards 6G: Multi-sensory XR and haptics, Connected industries and automation, Autonomous vehicles and swarm systems, and Extreme coverage. This, in turn, has given us the position to forecast target performance capabilities in the wireless and network domains.

Further, in chapter 3, we have identified which technologies we believe will contribute to meet these target capabilities, and we have created 10-year roadmaps towards 2030. A few of the technologies have been shortlisted and discussed in more detail.

In the wireless domain, important technologies must contribute to the push for higher frequencies and more energy efficiency. Advancements in AI/ML will enable the convergence of communications, imaging and processing. Meta-surfaces will be used to enable sophisticated beamforming and control the propagation environment, and further improve link quality and resource utilization. Energy-harvesting will be matured to support future super-massive IoT scenarios.

In the network domain, the system architecture will undergo a major re-structuring to enable cloud- and edge-native designs and a fully distributed infrastructure. Also, in this domain, AI will help to create a dynamically changing network, supporting resource usage optimization. The fusion of wireless and networking leads to the network becoming a fabric of resources, a platform for XaaS (anything as a service), which dynamically adapts to needs.

As next steps, the EMPOWER project will continuously follow, update and refine the roadmap towards the submission of the final version in November 2021. In the final edition, we also aim to provide recommendations on areas of priority and include risk analysis.

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