HORIZON 2020

ICT - Information and Communication Technologies

Deliverable D2.5

Final technology roadmap for advanced wireless

Project Acronym:	**EMPOWER**
Project Full Title:	**EMpowering transatlantic PlatfOrms for advanced WirEless Research**
Grant Agreement:	**824994**
Project Duration:	**42 months (Nov. 2018 - Apr. 2022)**
Due Date:	**30 November 2021 (M36)**
Submission Date:	**29 November 2021 (M36)**
Dissemination Level:	**Public**
Authors:	**Alain Mourad (InterDigital), Per Hjalmar Lehne (Telenor), Ole Grondalen (Telenor), Antonio de la Oliva (UC3M)**
Reviewers:	**Didier Bourse (Nokia Bell Labs France)**

Disclaimer

The information, documentation and figures available in this deliverable, is written by the EMPOWER project consortium under EC grant agreement 824994 and does not necessarily reflect the views of the European Commission. The European Commission is not liable for any use that may be made of the information contained herein.

Co-funded by the Horizon 2020 programme of the European Union

Executive Summary

This deliverable presents the final technology roadmap developed within the EMPOWER project. This final deliverable is presented in the form of updates to the previous technology roadmap presented in D2.4 [1].

These updates account for the latest development on 5G-Advanced and 6G from key international stakeholders such as the ITU-R WP5D Future Technology Trends on IMT-2030 [2] and the 6G-IA European vision for the 6G Network Ecosystem [3].

This final deliverable concludes the pioneering work on beyond 5G technology road mapping led by the EMPOWER project. This work has been validated through its high degree of alignment with the European [3] and American [4] 2030 wireless research agendas and the emerging global consensus in international bodies like the ITU-R [2] and NGMN [5].

Thanks to the EMPOWER roadmap and the engagement with 6G-IA and ETSI, ETSI has recently launched the very first pre-standard industry group on Reconfigurable Intelligent Surfaces (RIS) [13]. This group has attracted a significant interest from the industry and research community globally with over 30 organizations including prominent 3GPP industry stakeholders, and is currently chaired by InterDigital, the lead of the EMPOWER B5G technology roadmap. This has been recently celebrated as a success story by 6G-IA as reported in [14]. Similar pre-standardization groups are expected to emerge for technologies (e.g., high frequencies above 100 GHz) identified in the EMPOWER roadmap and aligned with the global consensus emerging in the ITU-R.

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
FRMCS	Future Railway Mobile Communication System
FPS	Frames per second
FTTR	Future Technology Trends
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
PIoT	Personal Internet of Things
RAN	Radio Access Network
RIS	Reconfigurable Intelligent Surfaces
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

Table of Contents

1. Introduction

The year 2021 was marked by a significant activity targeting consensus building on a global vision for 6G as well as future technology trends for enabling the use cases and service scenarios envisioned by 2030. A key development on this front has been the official launch by ITU-R in February 2021 of the IMT-2030 Vision and Future Technology Trends (FTTR), due to conclude in the Summer 2022 as shown in the timeline depicted in Figure 1 [2].

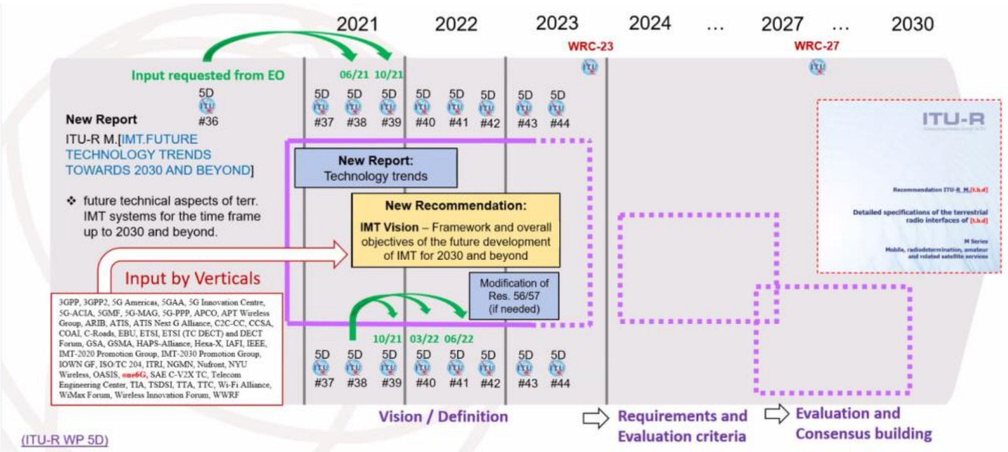

Figure 1: IMT process for systems beyond IMT-2020.

The ITU-R FTTR draft report has received significant contributions from all key stakeholders from all around the Globe, including Europe, North America, and Asia Pacific. Whilst the report is still in a draft mode with its public release due for June 2022, significant progress has been made towards achieving a global consensus on the key use cases, their key requirements, and the enabling technology trends.

EMPOWER partners namely InterDigital, Nokia, and Telenor, have been contributing to this ITU-R FTTR draft report. The insights gained from the current draft have been utilized in this EMPOWER final deliverable to:

- Validate our own EMPOWER technology roadmap [1];
- Provide a final update of our EMPOWER roadmap by accounting of the emerging global consensus on the requirements and technology trends as captured in the ITU-R FTTR draft report so far.

This final deliverable comes therefore to conclude our efforts in developing the EMPOWER B5G technology roadmap. The rest of this deliverable is structured as follows. Chapter 2 provides our final update on the target capabilities for future wireless networks. This is next followed in Chapter 3 with a final update on the technology trends for meeting the target capabilities. Chapter 4 finally draws our final conclusions.

2. Final 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, referred to as 5G-Advanced in 3GPP, 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]. There are a number of studies and Work Items on services and characteristics driving new requirements for the evolution of 5G [9] within domains as (not exhaustive):

- Tactile and multi-modality communication services;
- Low Power High Accuracy Positioning for Industrial IoT scenarios;
- Enhancements for cyber-physical control applications in vertical domains;
- Application layer support for Factories of the Future (FF);
- Future Railway Mobile Communication System (FRMCS);
- NR positioning enhancements;
- Communication Service Requirements for Critical Medical Applications;
- Supporting Uncrewed Aerial Systems (UAS);
- Mission critical communication.

From the full list of studies, one can identify the following service categories as key drivers for the evolution of the 5G KPIs in the short-medium terms [10]:

- 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;
- Mission critical 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

6G will have to meet a lot more goals than just providing fast mobile Internet access, like support for digital twinning, immersive communication, cognition and connected intelligence to enable convergence of the physical, human and digital worlds [3].

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 [10][11]:

- 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) [15]. Many future applications in this domain require to run on tight and deterministic latency constraints, which means jitter has to be improved. In addition to user data rate, as this new category grows and applications expand, stringent requirements on Energy Efficiency and Connection Density 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 and efficiency improvements. 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 [16]. Wireless will need to rise to fiber-like performance not only in speed but in latency, reliability and availability, meaning that 6G needs to provide a trustworthy infrastructure as a basis for societies of the future. Positioning accuracy (cm-level) is also emerging as a critical new requirement 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 [3][17]. 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 5G-Advanced and 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. To succeed, 6G has to be both affordable and scalable, and that can probably only be ensured if 6G becomes a global standard. 6G also has to be manageable, thus the number of options included should be carefully chosen only among those with a real market potential [3][4]. 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 [11]. The high intensity color means high impact, medium intensity means medium impact, and low intensity means low impact in terms of the level of enhancement required on today's 5G KPIs.

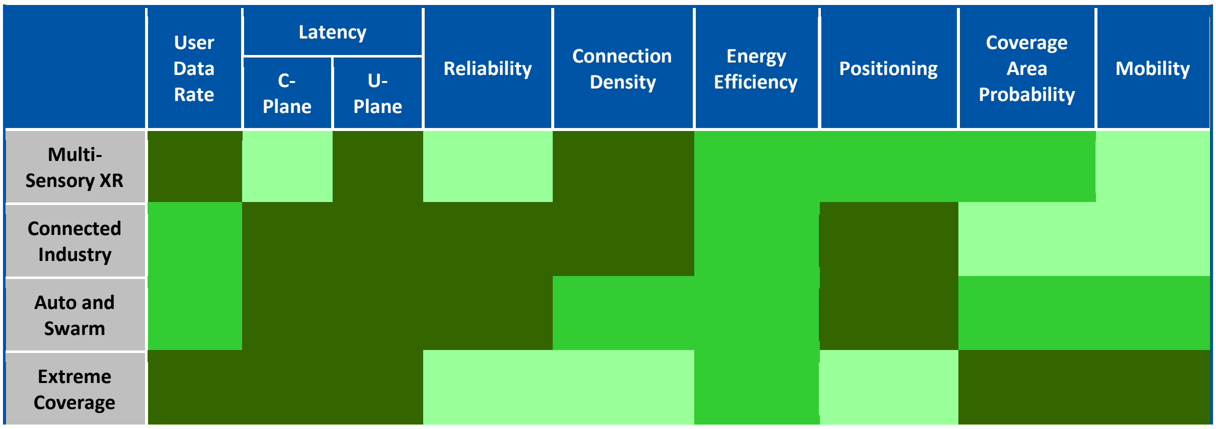

Figure 2: Heatmap impact of emerging use cases on 5G KPIs. Intensity refers to the Impact (e.g. High intensity means High impact).

Based on the insights gained from the current ITU-R FTTR draft report, the use cases and service scenarios under discussion include [2]:

- Holographic communication, tactile internet and VR/AR-based sensing;
- Industry 4.0, fully autonomous driving and navigation, and smart rail-systems;
- UAV-based systems, integrated satellite and radar networks;
- Smart cities and massive IoT;
- Extreme low energy networks, internet of bio-things and clock-free systems.

The above five categories of services from the ITU-R FTTR draft aligns to a large degree with our own abovementioned EMPOWER categorization of the services driving the evolution 5G to 6G. This validates our vision of the services and use cases driving the new capabilities and requirements in the short-, medium- and long-term evolution of 5G.

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.

In Figure 3, we highlighted in red the current assumptions in ITU-R FTTR draft report which slightly differ from our own forecast in the previous technology roadmap. The capabilities with no red highlight are aligned perfectly with what is in the current state of the ITU-R FTTR draft report. This validates our own forecast of the targeted capabilities from the previous EMPOWER roadmaps.

	IMT-2020	IMT-2030
Spectrum	Up to 100 GHz	Carrier frequencies up to 300 GHz
Bandwidth	At least 100 MHz; Up to 1 GHz	Single channel bandwidth above 10 GHz
Peak data rate (DL/UL)	20 Gbps (DL) 10 Gbps (UL)	Peak data rate exceeding 200 Gbps (downlink) and 100 Gbps (uplink) Update: 1 Tbps (current IMT-2030 assumption)
User data rate (DL/UL)	100 Mbps (DL) 50 Mbps (UL)	Average user data rate exceeding 1 Gbps (downlink) and 0.5 Gbps (uplink) for multi-sensory XR and volumetric media streaming
U-plane Latency	4 ms for eMBB 1ms for URLLC	U-plane latency below 0.5 ms for connected industries, autonomous vehicles and tactile use cases Update: 25 us to 1 ms (current IMT-2030 assumption)
C-Plane Latency	Below 20 ms (10 ms desired)	Control plane latency below 5 ms for connected industries, autonomous vehicles and tactile use cases
Reliability	Up to 5 nines	Reliability up to 8 nines for connected industries and autonomous vehicles
Connection Density	1 device per sqm	Connection density up to 10 devices per sqm (10m devices per km2) for ultra-massive sensor networks
Energy Efficiency	Qualitative	Terminal and network energy efficiencies up by 1000x today's values 5G system Update: 100 to 1000x (current IMT-2030 assumption)
Positioning Accuracy	NA	Positioning accuracy below 5 cm (indoor) and 10 cm (outdoor) helped by joint sensing and communications
Mobility	Up to 500 kmh	Mobility exceeding 1000 kmh for flying objects (e.g. airplanes) supported by the integration with non-terrestrial networks

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. The current assumption in the ITU-R FTTR is above 1000 Gbps in the downlink;
- 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 100 GHz 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 5 ms. 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 underlying their importance for 6G especially with the sustainability development goals set out by the ITU.

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.

	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. Final Update on Technology Trends

This chapter provides an update on the wireless and network technology trends for the short- and medium-term evolution of 5G (a.k.a. 5G-Advanced) and longer term 6G. These are positioned as enabling technologies to meet the 6G 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.

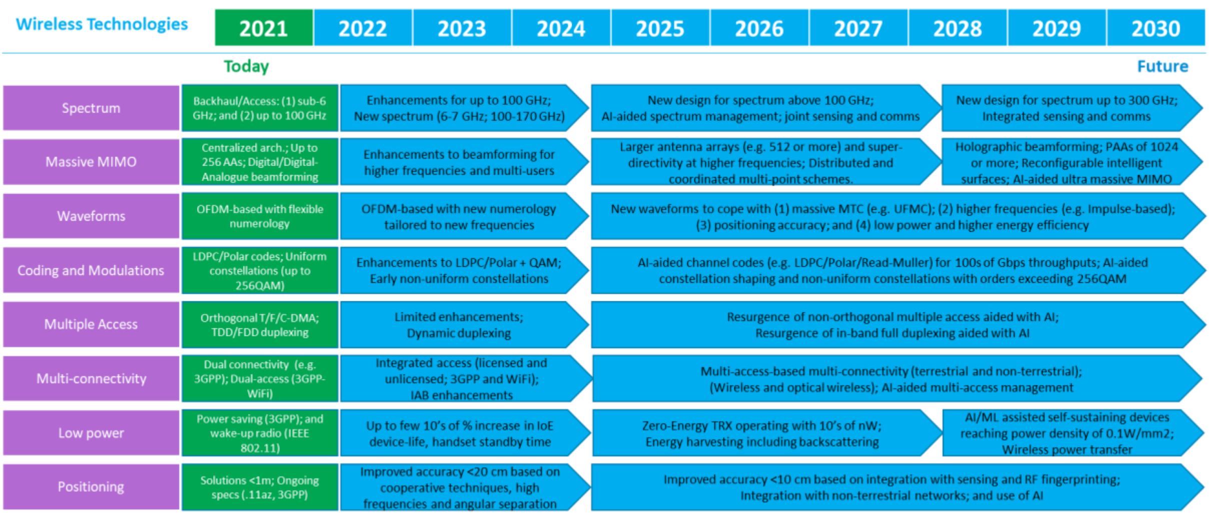

Figure 5: Wireless Technologies Roadmap.

In the ITU-R FTTR report, the technologies targeted at enhancing the radio interface include:

- Sub-THz (Above 100 GHz) frequencies;
- Extreme MIMO;
- Multiple physical dimension transmission including reconfigurable intelligent surfaces (RIS);
- Advanced modulation, coding and multiple access schemes;
- Co-frequency co-time full duplex communications;
- Ambient backscatter communication.

The above shows a great deal of alignment with the technology trends captured in Figure 5.

Below we have updated the four wireless technologies shortlisted in the previous roadmap in D2.4 [1]:

- 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 necessity for achieving average user data rates >1Gbps. Even if potential bands for 6G also include existing 5G and prior generation bands, upper mm-wave (100-300 GHz) and THz band (300 GHz – 3 THz) are recognized of interest to achieve the Tbps data rates and support data intensive applications like extended reality (XR) [12]. 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
72 GHz-100 GHz: Mature precommercial TX tech. with applications in NGI, XR & JCS. Throughputs in excess of 50 Gbps forecast.	**Above 100 GHz:** Lab grade reference designs & testbeds. Future applications in NGI, XR & JCS. Throughputs in excess of 100 Gbps.	**Up to 300 GHz:** Still mostly academic with experimental TX designs & testbeds. Throughputs up to 1000 Gbps.

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 60 GHz 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

This is worth noting that thanks to the EMPOWER roadmap and its engagement with the various stakeholders noticeably in 5G-IA, ETSI has recently launched the very first pre-standard industry group on Reconfigurable Intelligent Surfaces (RIS) [13]. This ETSI RIS ISG targets at streamlining the European and global research on RIS technology and paving the way for the technology specification in future wireless standards (e.g. 3GPP). This group has attracted significant interest from the industry and research community. This is chaired by InterDigital, the lead of the EMPOWER B5G technology roadmap. This has been recently celebrated as a success story by 6G-IA as reported in [14].

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, etc. Beginning of standards efforts in the study item phase (e.g., IEEE 802.11bf)	Mature Standards for joint communication and Sensing, sensor fusion integrated into the wireless framework, emergence of first sensing and communication chipsets	Full support of sensing, communications, imaging and positioning in integrated PHY 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. In a broad perspective, the challenge is to harvest energy from any sustainable source in the environment, which for example can be RF, mechanical or solar. 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 1 pJ/bit consumption; and 2) AI driven dynamically reconfigurable radio elements leveraging multi-band, multi-RAT and meta-material antenna technology, while balancing ever conflicting KPIs, like 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.	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 1 pJ/bit with power density of 0.1 W/mm^2.

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 2021 to 2030. For each technology, a reference of the current (2021) 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.

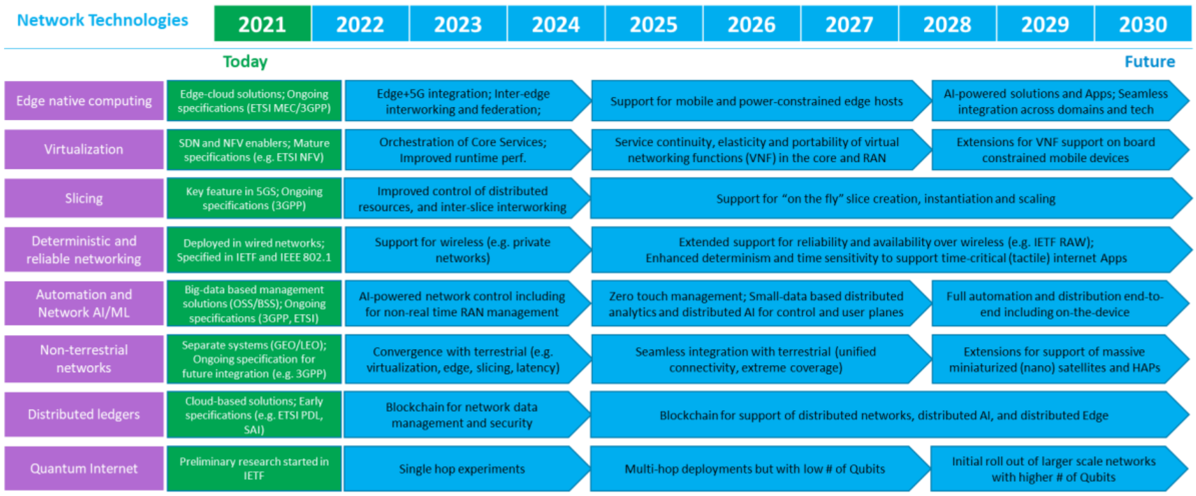

Figure 6: Network Technologies Roadmap.

In the ITU-R FTTR report, the technologies targeted at enhancing the future network include:

- Resilient and soft network;
- Digital Twin networking;
- Convergence of communication and computing;
- Intelligent networks and services;
- Integration of terrestrial and non-terrestrial networks;
- Native security, privacy.

The above shows a great deal of alignment with the technology trends captured in Figure 6.

Below we have updated the four network technologies shortlisted in the previous roadmap in D2.4 [1]:

- 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. An important aspect that must be addressed is that operators and users often require predictable performance and performance guarantees, which can be a challenge for pure AI/ML based solutions. Hybrid solutions, such as combined analytical and machine learning modelling, will therefore be needed.

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.

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. Lower cost per bit is also an important argument; a study suggests that a 1.18 Pbps VLEO system is 45x cheaper than a terrestrial system [19].

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 and further built on 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. Major communications vendors have also adopted the Cloud Native paradigm for their core/edge developments. Adopting Cloud Native approaches yields to higher flexibility and easier development of new functions, reducing the TCO of a solution by enabling the constant upgrade of functionality. Therefore, adopting this development approaches is critical for the evolution to 5G towards 6G. In this update to the EMPOWER Technology Roadmap, the challenge continues to be in the RAN, with continuous work from alliances as Open-RAN to open vendor interfaces to achieve a fully beyond 5G Virtualized RAN. 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. The current trend towards reducing the power consumption of network services, the need of placing computational resources even closer to the end user and the continuous improvement of AI capabilities on end devices, must be considered when developing the next generation of the hyper-distributed edge. 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. Current orchestration approaches, largely based on centralized control nodes will not hold for the hyper-distributed edge, requiring of novel distributed and liquid approaches able to coordinate volatile resources in a distributed manner. The new hyper-distributed edge will not be composed of mainly powerful computers as nowadays, but it will be composed by an amalgam of constrained devices of different nature and capabilities. 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 with the case of Cloud Native, this new hyper-distributed edge will need a new way of realizing applications, able to hide the complexity from the developer. This new paradigm, known as EdgeOps will need of study to reach the maturity level of current Cloud Native and DevOps frameworks. As a result, this may not happen until we turn the page to 6G [3][4][5]. 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 Application of DevOps to the Edge, to realize the EdgeOps concept.	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 3) Design of new orchestration and management systems for hyper-distributed edge systems.	Ubiquitous Edge Native Application Architectures operating seamlessly across multi-access networks and domains (cloud / telco edge / device edge)

4. Conclusions

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

Since the very first EMPOWER technology roadmap was published in October 2019, followed by a public consultation, the attention to 6G has increased significantly. Today, all global stakeholders are working together for building consensus on a global vision and technology trends for future wireless networks by 2030 including noticeably in global forums such as ITU-R, NGMN, ETSI, the 3GPP, IEEE and the IETF. The global consensus on the use cases, technology trends, and initial requirements is expected to emerge next year (2022) especially with the public release of the ITU-R vision and future technology trends report (FTTR) for IMT systems beyond IMT-2020 (a.k.a. IMT-2030).

By following closely and contributing actively to the industry efforts towards building such consensus from the onset, the EMPOWER consortium prides itself for its sounds vision and roadmap which has been validated through benchmarking with the status into the ITU-R IMT-2030 draft report. All key use cases identified in EMPOWER for driving the evolution from 5G to 6G, such as Multi-sensory XR and haptics, connected industries and automation, autonomous vehicles and swarm systems, and extreme coverage, have been adopted so far by the current ITU-R FTTR draft as key drivers for IMT-2030.

Equally, the target capabilities required to support all these use cases as forecasted in the EMPOWER roadmap have been to a high degree aligned with the current target capabilities laid out in the ITU-R FTTR draft report for IMT-2030. The same applies to the key technology trends such as the push for higher frequencies and more energy efficiency including energy harvesting, convergence of communications, imaging and processing, reconfigurable intelligent surfaces, spatial communications, and AI/ML.

Thanks to the EMPOWER roadmap and early engagement with the various stakeholders in particular with 6G-IA and ETSI, ETSI has recently launched the very first pre-standard industry group on Reconfigurable Intelligent Surfaces (RIS) [13]. This ETSI RIS ISG targets at streamlining the European and global research initiatives on RIS technology and paving the way for its future specification in global standards such as 3GPP. This group has attracted a significant interest from the industry and research community globally with over 30 organizations including prominent 3GPP industry stakeholders, and is currently chaired by InterDigital, the lead of the EMPOWER B5G technology roadmap. This has been recently celebrated as a success story by 6G-IA as reported in [14]. This is also expected that similar pre-standardization groups will emerge for technologies identified in the EMPOWER roadmap and aligned with the global consensus emerging in the ITU-R, such as higher frequencies (Above 100 GHz).

References

[1] Alain Mourad, Per H Lehne and Antonio De La Oliva. "Second Technology Roadmap for Advanced Wireless", Deliverable D2.4, EMPOWER project, EU grant no 824994. October 2019. Online: https://www.advancedwireless.eu/

[2] ITU-R Working Party 5D (WP 5D) – IMT Systems, Online : https://www.itu.int/md/R19-WP5D-C/en

[3] European Vision for the 6G Network Ecosystem, Online: https://5g-ppp.eu/wp-content/uploads/2021/06/WhitePaper-6G-Europe.pdf

[4] 5G Americas White Paper "Mobile Communications Towards 2030 - Next Generation Efforts in Wireless Communications Move Forward", 22 November 2021, Online: https://mailchi.mp/5gamericas/verticalusecases-2689653?e=983475a899

[5] Next Generation Mobile Networks (NGMN) Online: https://www.ngmn.org/

[6] H2020 ICT-52 HEXA-X project, Online: https://hexa-x.eu/

[7] 3rd Generation Partnership Project. "Service Requirements for the 5G System", 3GPP TS 22.261 V18.1.1 (2021-01)

[8] 3rd Generation Partnership Project. "Service requirements for cyber-physical control applications in vertical domains", 3GPP TS 22.104 V17.4.0 (2020-10)

[9] 3rd Generation Partnership Project. "3GPP List of Work Items", Online: https://www.3gpp.org/DynaReport/WI-List.htm

[10] Alain Mourad, "Technology Trends Towards 6G", 6GiC, University of Surrey, 5 February 2021, Online: https://www.slideshare.net/AlainMourad/technology-trends-towards-6g

[11] NetWorld2020 SRIA, "Strategic Research and Innovation Agenda 2021-27", September 2020, Online: https://www.networld2020.eu/sria-and-whitepapers/

[12] Pärssinen, A., Alouini, M., Berg, M., Kuerner, T., Kyösti, P., Leinonen, M. E., Matinmikko-Blue, M., McCune, E., Pfeiffer, U., & Wambacq, P. (Eds.). (2020). "White Paper on RF Enabling 6G – Opportunities and Challenges from Technology to Spectrum" [White paper]. (6G Research Visions, No. 13). University of Oulu. Online: http://urn.fi/urn:isbn:9789526228419

[13] ETSI RIS ISG, https://portal.etsi.org/TB-SiteMap/RIS/List-of-ISG-RIS-Members-and-Participants

[14] 5G-IA success story, "Reconfigurable Intelligent Surfaces for B5G/6G - An ETSI ISG RIS Proposal", Online : https://global5g.org/online-tool-standards-tracker/reconfigurable-intelligent-surfaces-b5g6g-etsi-isg-ris-proposal

[15] ABI Research. "Augmented & Virtual Reality Research Service". Online: https://www.abiresearch.com/market-research/service/augmented-virtual-reality/

[16] 5G Alliance for Connected Industries and Automation (5G-ACIA), Online: https://www.5g-acia.org/

[17] 5G Automotive Association (5GAA), Online: https://5gaa.org/

[18] DoCoMo. "DOCOMO Conducts World's First Successful Trial of Transparent Dynamic Metasurface". Press Release, 17 January 2020, Online: https://www.nttdocomo.co.jp/english/info/media_center/pr/2020/0117_00.html

[19] BBC, "Satellite boom attracts technology giants", BBC News, 29 January 2021, Online: https://www.bbc.co.uk/news/business-55807150