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ICT - Information and Communication Technologies

Deliverable D2.3

Update on Trends, Status and Plans for advanced wireless

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Executive Summary

The EMPOWER project, since its launch in November 2018, has been following closely all developments around 5G and its evolution in the short, medium and long terms. This is with the aim to develop a comprehensive advanced wireless technology roadmap synthesizing all the views from all the stakeholder R&D communities.

This update of the trends in wireless technologies, WP2 deliverable D2.3, is following up the first trend report from 2019, D2.1. It also captures the feedback from the consultation on the first EMPOWER B5G technology roadmap, D2.2 from October 2019.

The following summarizes the key topics presented in this deliverable:

1) Identification of key stakeholders in the wireless R&D communities, in Europe, the USA, in Asia, and globally, covering various forums, alliances, and organizations that have been followed by the EMPOWER roadmap team to capture and analyse the trends.
2) Targeted KPIs for the evolution of 5G in the short, medium and long terms, based on the consultation of the first EMPOWER wireless technology roadmap.
3) B5G wireless technology trends captured from the studies around the next batch of future wireless standard releases in 3GPP (e.g. Release 17 and Release 18), and in IEEE (evolution of IEEE 802.11 and IEEE 802.15).
4) Longer term B5G/6G wireless technology trends captured from the scientific visions around 6G, which are deemed more disruptive and less mature for consideration in the forthcoming wireless standards.
5) Wireless spectrum trends for 5G and B5G including trends for unlicensed spectrum, dedicated spectrum for verticals, spectrum sharing, and very high frequencies (up to THz).

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Introduction

The year 2019 saw the first commercial rollouts of 5G networks in several regions and countries, noticeably in Europe, the USA, South Korea, Japan and China. According to GSMA Intelligence [1] in March 2020, 5G is live in 24 markets and in 2025; it is believed that 5G will account for 20% of global connections. According to the EU 5G Observatory [2], 11 of the member states (+UK) have published national 5G roadmaps.

Step-by-step in the different countries, spectrum auctions have been carried out, infrastructure equipment have been supplied, 5G devices have been shipping, and operators have started to offer 5G subscription plans to the end users primarily for super-fast broadband services. In the light of this 5G commercial fever, the global wireless research and development (R&D) communities have started actively to lay out their agendas for what is coming up next beyond 5G (B5G). These agendas varied in time scales in line with the inherently different time horizons of the various wireless R&D communities, ranging from longer term agendas targeting 6G as set out by the more visionary research forums, down to shorter term agendas targeting the next immediate enhancement of current 5G specifications as set out by the related standardization organizations.

The EMPOWER project, since its launch in November 2018, has been following closely all these developments around Beyond 5G, from the shorter term to the longer term, with the aim to develop a comprehensive advanced wireless technology roadmap synthesizing all the views from all stakeholder R&D communities.

This deliverable, D2.3, is an update of the trends first presented in 2019 in D2.1 [2]. It also captures some of the feedback from the consultation on the first technology roadmap in deliverable D2.2 [4]. Further analysis of this feedback will be the foundation for the next edition of the EMPOWER B5G roadmap, D2.4, to be released in October 2020.

This deliverable is structured around four key chapters as follows:

- Chapter 1 provides the list of key wireless R&D stakeholders considered in this deliverable to capture the different views and trends.
- Chapter 2 provides the trends captured on B5G key performance indicators (KPIs) and requirements.
- Chapter 3 focuses next on the B5G technology trends captured from the wireless research forums and standardization organizations.
- Chapter 4 completes the overall picture by providing the trends in spectrum regulation, and includes highlights from the ITU-R World Radiocommunication Conference 2019 (WRC-19).

Conclusions are then drawn in a final section.

1. Key Wireless R&D Stakeholders

This chapter presents the list of key wireless R&D stakeholders considered in this deliverable to capture the different views and trends. Some 25 stakeholders have been identified in the EU, US, and globally. The stakeholders have been classified in three categories: i) Research programmes; ii) Industry and standard forums; and iii) Spectrum regulation organizations.

1.1 Research Programmes

Table 1-1 gives a list of the top 14 wireless research programmes considered in analysing the trends for B5G.

Table 1-1: 5G/B5G research programmes.

No	Stakeholder	Region	Short description
1	EC H2020 5G-PPP ICT-17, 18, 19, 20, 21, 22, 23, 41, 42, 52	Europe	Programme already in its phase 3 focused on 5G experimental validation and starting research on beyond 5G (paving the way for Horizon Europe). 25+ projects were selected across the ICT-17, 18, 19, 20, 21, 22 and 23 calls. Some 25+ projects are expected across the calls 41, 42, 52 and 53.
2	EC H2020 THz cluster	Europe	Cluster of 6 projects mostly focused on THz, launched in 2017 and due for completion in 2020.
3	NetWorld2020 ETP	Europe	EU technology platform issuing network technologies strategic research agenda for EU research programmes like H2020, HEU
4	COST IRACON	Europe	COST action focused on radio communication research for 5G and beyond. The action has ended and the Final report submitted in April 2020. A follow-up action proposal was submitted in September 2019, but rejected in the evaluation round in March 2020. It will probably be reworked and resubmitted later in 2020.
5	6G-Flagship	Europe Finland	Finnish research programme on 6G, launched in 2018 and running for 7 years.
6	US PAWR	USA	US-IGNITE NSF programme focused on platforms for advanced wireless research, including 4 projects, 3 already launched from phase 1 and 2, and 1 additional expected from phase 2. Programme launched in 2018 until 2024.
7	US DARPA Colosseum	USA	DARPA's massive testbed for researchers to build and test autonomous, intelligent and collaborative wireless technologies, including the ones developed in the DARPA Spectrum Challenge.
8	US DARPA Spectrum Challenge	USA	DARPA international research challenge on collaborative Intelligent Radio Networks (Using Artificial Intelligence).
9	WWRF	Global	Wireless World Research Forum including over 50 industry and university members mostly from Europe and Asia.
10	5G IA	Europe	The 5G Infrastructure Association represents the Private Industry side in the European H2020 5G Public-Private Partnership (5G PPP), and provides the business dimension on top of the technical work from European Research.
11	5GMF	Japan	The Fifth Generation Mobile Communications Promotion Forum conducts research & development concerning 5G as well research and studies pertaining to standardization.

No	Stakeholder	Region	Short description
12	5GForum	South Korea	A private-public research organization in South Korea targeting the development and promotion of 5G and beyond mobile technologies.
13	IMT-2020 (5G Promotion Group)	China	IMT-2020 (5G) Promotion Group, established by three ministries in China, is the major platform to promote the research of 5G in China. Its members include the operators, vendors, universities, and research institutes in the field of mobile communications.
14	5G Brasil Project	Brasil	A private association with 65 members from the telecommunications sector in Brasil organized as an autonomous project under the Telebrasil umbrella.

1.2 Industry and Standards Forums

Table 1-2 gives a list of the top 11 industry and standards forums considered in analysing the trends for wireless 5G/B5G.

Table 1-2: 5G/B5G industry and standards forums.

No	Stakeholder	Region	Short description
1	3GPP	Global	3GPP is the global standard development organization for cellular networks (3G/4G/5G). 3GPP develops the specifications. Main groups are Radio Access Networks (RAN), Core and Terminals (CT) and Service and System Aspects (SA).
2	IEEE 802	Global	IEEE 802 develops global standards for local and metropolitan area networks. The 802.11 (WLAN) and 802.15 (WPAN) are the most relevant working groups dealing with advanced wireless systems.
3	ETSI	Europe Global	ETSI, in addition to developing and ratifying various standards such as 3GPP and DVB, hosts exploratory activities on emerging technologies for ICT-enabled systems.
4	IETF/IRTF	Global	IETF is an open standards organization, which develops and promotes voluntary Internet standards, in particular the standards that comprise the Internet protocol suite.
5	ITU-T	Global	ITU-T develops recommendations of standards in the global infrastructure of ICT. In addition to specification study groups, ITU-T has also Focus Groups that are now widely used as an exploration of emerging ICT technology trends that might lead to future standards.
6	O-RAN	Global	O-RAN (Operator Defined Next Generation RAN Architecture and Interfaces) is an alliance of members led by operators committed to develop the foundations of future RANs based on intelligence and openness. O-RAN operates 6 technical workgroups including both reference design and implementations.

No	Stakeholder	Region	Short description
7	NGMN	Global	NGMN is an alliance of members led by operators which mission includes: 1) establishing clear functionality and performance targets as well as fundamental requirements for deployment scenarios and network operations; and 2) giving guidance to equipment developers and standardization bodies, leading to the implementation of a cost-effective network evolution
8	GSMA	Global	GSMA (GSM Association) represents the interests of mobile operators worldwide, uniting more than 750 operators with almost 400 companies in the broader mobile ecosystem, including handset and device makers, software companies, equipment providers and internet companies, as well as organizations in adjacent industry sectors.
9	ATIS	USA	ATIS (Alliance for Telecommunications Industry Solutions) is a standards organization accredited by the American National Standards Institute (ANSI). It develops technical and operational standards and solutions for the ICT industry. It is the North American Organizational Partner for the 3rd Generation Partnership Project (3GPP).
10	ITRS	Global	ITRS (International Technology Roadmap for Semiconductors) represents best opinion on the directions of research and timelines up to about 15 years into the future for the semiconductor technology. ITRS is developed by a group of semiconductor industry experts from the sponsoring organizations, which include the Semiconductor Industry Associations of the United States, Europe, Japan, China, South Korea and Taiwan.
11	5G Americas	USA	5G Americas is an industry trade organization of telecommunications service providers and manufacturers.

1.3 Spectrum Regulation Organizations

Table 1-3 gives a list of the top five spectrum regulation forums considered in analysing the trends for B5G.

Table 1-3: 5G/B5G spectrum and regulator forums.

No	Stakeholder	Region	Short description
1	ITU-R	Global	ITU-R (The International Telecommunications Union Radio Sector)'s mission is to ensure rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, and to carry out studies and adopt recommendations on radiocommunication matters. The main decisions are taken every three to four years at the World Radiocommunication Conference (WRC).
2	CEPT/ECC	Europe	The ECC (European Communications Committee) develops policies on electronic communications activities in the European context, taking account of European and international legislations and regulations. The ECC, through the ECO, publishes Reports, Recommendations and Decisions, which are put forward for public consultations.

3	RSPG	Europe	RSPG (Radio Spectrum Policy Group) is a high-level advisory group that assists the EC in the development of radio spectrum policy. RSPG publishes 'Opinions' and 'Reports', both, which are subject to public consultations. RSPG is the most important body in the EU policy on Wireless Europe, part of the Digital Single Market policy.
4	FCC	USA	FCC (Federal Communications Commission) is the Authority for telecommunications regulations in the USA, where spectrum regulations is one of the key responsibilities.
5	OFCOM	UK	Ofcom is the UK's regulator for communications services including broadband, home phone and mobile services, as well as TV and radio. Airwaves spectrum regulation is one of the key responsibilities.

2. Update on B5G Key Performance Indicators

This chapter presents an update on the B5G KPIs developed in deliverable D2.1 [2]. This update accounts for the feedback obtained from the public consultation run by EMPOWER on the B5G baseline roadmap [4]. The update also accounts for emerging positions from global vendors and operators on the KPIs targeted in 6G.

2.1 Overview of EMPOWER B5G KPIs

In its baseline roadmap [4][5], EMPOWER presented forecasts on the evolution of 5G KPIs in the short (SEVO), medium (MEVO) and long (LEVO) terms, as depicted in Figure 2-1.

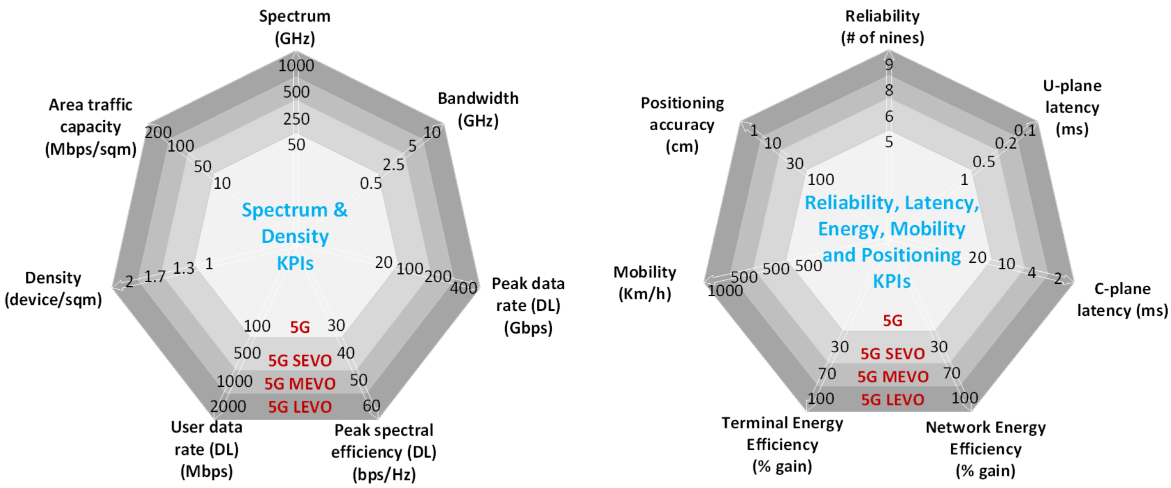

Figure 2-1: EMPOWER forecast of 5G KPIs evolution in the short, medium and long terms.

The above forecasts have been obtained following a preliminary analysis of emerging use cases and their requirements together with assumptions on the pace of wireless technology advancements published in [5]. The 5G KPIs evolution towards 6G in above Figure 2-1 is summarized in the form of trends below:

- Spectrum with leap jumps above 100 GHz all the way up to THz
- Single channel bandwidth expansion from 400 MHz today up to 10 GHz
- Peak data rate moving to a few 100s of Gbps
- User data rate scaling up to a few Gbps
- Connections density doubling to 2 devices per sqm
- Reliability gradually increasing to reach highs of up to 9 nines
- U-plane latency down to a fraction of a millisecond
- Energy efficiency (network and terminal) improving towards 100% gains compared to the values obtained with 5G system as of 3GPP Release 16
- Positioning accuracy improving to a few centimeters
- Mobility support increasing to up to 1000 km/h speed

2.2 Overview of EMPOWER B5G Roadmap Consultation

Following the release of its baseline roadmap [4][5], the EMPOWER project has launched a publication consultation [6] aiming at collecting the wireless research community feedback and using this feedback to validate and refine the EMPOWER roadmap in its future releases. The consultation opened beginning of February 2020 and run until end of March 2020. The consultation was presented in the form of a questionnaire survey spanning four main areas as follows i) KPIs evolution; ii) Technology trends; iii) Experimental challenges; and iv) Roadmap refinement. A total of 26 questions were put forward to the community for feedback and inputs.

A total of 63 respondents shared their feedback with a rough split of the demographic between universities and research institutes (60%), and the industry (40%). The respondents were from various countries across Europe, but also North America (USA, Canada) and South East Asia (China, Taiwan, South Korea).

The full results of the consultation will be subject for a future publication. In this deliverable, we only provide a snapshot from the consultation specific to the KPIs evolution.

2.3 Update on KPIs

This section presents the update on the KPIs from section 2.1 above. The update accounts for the feedback gained from the EMPOWER consultation on a selected set of seven out of the 14 KPIs presented in Figure 2-1. The update also accounts for emerging 6G positions from key stakeholders as recently published and presented at the 6G Summit 2020 in March 2020 [7][9-12].

2.3.1 Spectrum

Figure 2-2 shows the distribution of the feedback received on spectrum from where it stands today in 5G (up to 52.6 GHz). It is clear from Figure 2-2 that a noticeable majority (70.77%) foresees an evolution of spectrum above the 100 GHz cap. With regard to the question how far above 100 GHz will the spectrum evolve in the next 10 years, a clear majority (50.77%) casted the view of spectrum evolution up to 500 GHz, whereas a minority (20%) casted a more ambitious view for spectrum to reach as high as 1 THz (1000 GHz).

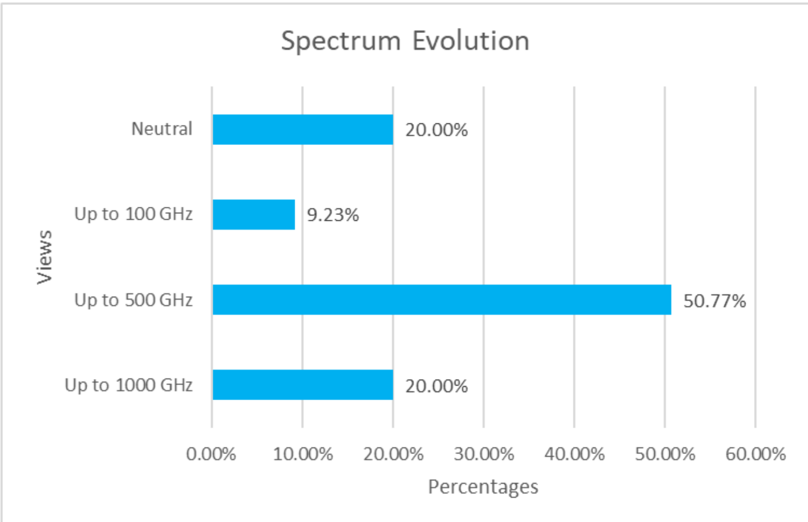

Figure 2-2: Views on spectrum evolution from EMPOWER consultation.

The above findings from the EMPOWER consultation aligns well with recent positions emerging from global stakeholders. Noticeably, global vendors such as Ericsson, Nokia and Huawei, and operator NTT DoCoMo, all shared the view that spectrum will evolve to reach a few hundred GHz up to the limit of 500 GHz [8, 9, 10 and 11]. The academic research community view however was more ambitious claiming easy sailing up to 700 GHz, as claimed in the keynote of Prof Ted Rappaport from NYU Wireless at the 6G Summit 2020 [12].

In conclusion, there is a clear trend in spectrum evolution breaking the present 5G cap of 100 GHz, and making leap jumps to multiple hundreds of GHz, from 200 up to 1000 GHz. The exact value of the new cap in 6G, whether it is 300, 500, 700 or 1000 GHz, is something that is impossible to assert at this point of time.

2.3.2 User data rate

Figure 2-3 shows the distribution of the feedback received on user data rate evolution. It is clear from Figure 2-3 that an overwhelming majority (98.39%) foresees an increase in the user data rate from 100 Mbps in 5G today to reach between a few hundred (50%) or a few thousand (48.39%) Mbps in the long run towards 6G. This aligns with EMPOWER forecast in section 2.1 for the user data rate to evolve from a few hundred Mbps in the short term to reach above 1 Gbps in the longer term.

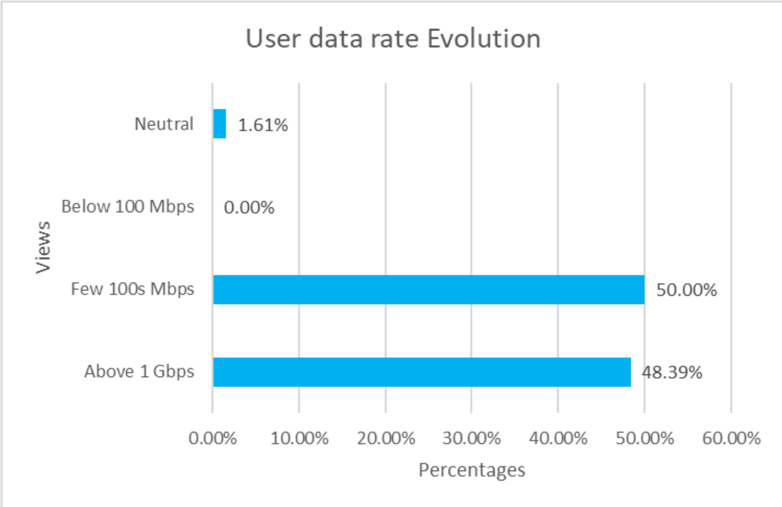

Figure 2-3: Views on user data rate evolution from EMPOWER consultation.

2.3.3 Connection density

Figure 2-4 shows the distribution of the feedback received on connection density evolution. It is clear from Figure 2-4 that an overwhelming majority (87%) foresees the connection density to double or more from today's 5G target of 1 device per square metre. The majority (56.45%) aligns with EMPOWER forecast in section 2.1 that it will nearly double, whereas nearly a third envisioned that it will more than double in the longer run towards 6G. Industry stakeholders like NTT DoCoMo [8], Nokia [9] and Huawei [11] both shared an ambitious forecast of the connection density in 6G multiplying by 10 times today's 5G target to reach 10 devices per square metre (10 million devices per km^2).

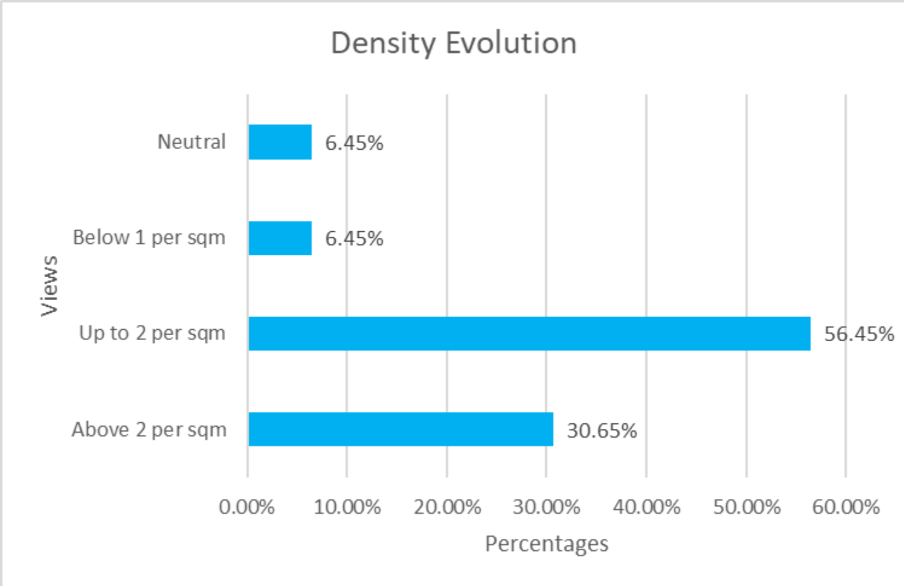

Figure 2-4: Views on connection density evolution from EMPOWER consultation.

2.3.4 Reliability

Figure 2-5 shows the distribution of the feedback received on reliability evolution. It is clear from Figure 2-5 that a clear majority (79%) foresees the reliability reaching new levels up to 8 nines (66.13%) and even above 9 nines (12.90%), compared to 5 nines in 5G today. In addition to the consultation, NTT DoCoMo [8] and Huawei [11] expressed recently in their respective 6G visions a forecast for reliability reaching up to 7 nines compared to 9 nines by Nokia [9]. A target of 8 nines in the long run appears therefore statistically as a reasonable fit.

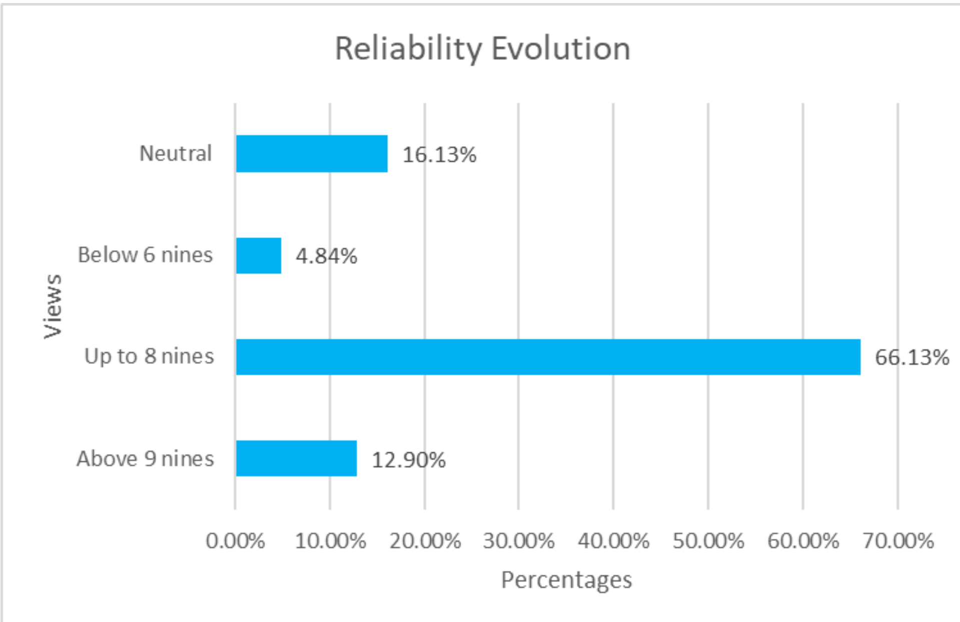

Figure 2-5: Views on reliability evolution from EMPOWER consultation.

2.3.5 Latency

Figure 2-6 shows the distribution of the feedback received on end-to-end user-plane latency evolution. It is clear from Figure 2-6 that a clear majority (86%) foresees the latency reaching new levels down to less than 1 ms in 5G today. A noticeable majority (63.49%) envisioned the new threshold to be 0.5 ms whereas some 25.40% shared the view on the threshold to be as low as 0.1 ms in line with Nokia [9] and Huawei [11] positions presented recently at the 6G Wireless Summit 2020.

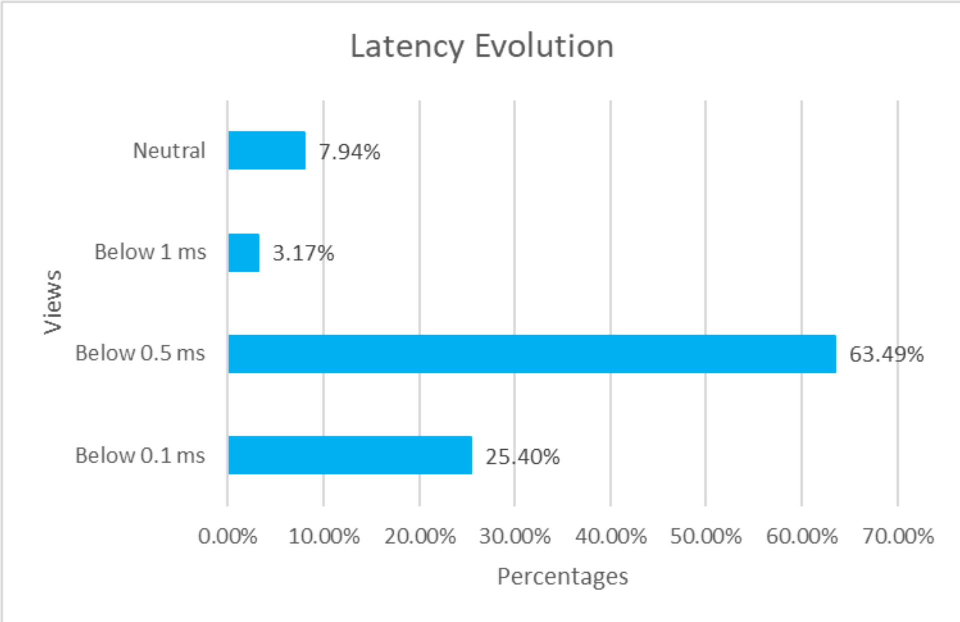

Figure 2-6 : Views on latency evolution from EMPOWER consultation.

2.3.6 Energy Efficiency

Figure 2-7 shows the distribution of the feedback received on energy efficiency evolution. It is clear from Figure 2-7 that a clear majority (90%) foresees the energy efficiency (both network and terminal) to improve with gains between 30%-70% (59.68%) and above 100% (30.65%) compared to 5G today. Huawei in their keynotes at the 6G Summit 2020 anticipated the energy efficiency to multiply by 100 times the present value in 5G today [11]. This also goes in line with the views expressed by major operators, manufacturers/vendors, EC and Members States Public Authorities stressing the importance of Energy Efficiency and Sustainability for the evolution of ICT and Networks. This is noticeably captured in the current EC Green Deal [13].

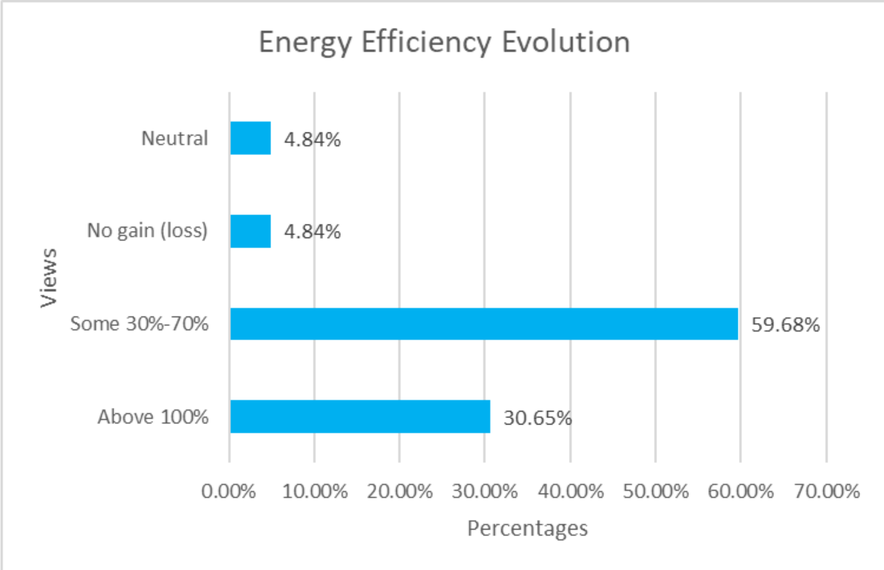

Figure 2-7 : Views on energy efficiency evolution from EMPOWER consultation.

2.3.7 *Positioning accuracy*

Figure 2-8 shows the distribution of the feedback received on positioning accuracy evolution. It is clear from Figure 2-8 that a clear majority (87%) foresees the positioning accuracy to improve significantly down to below 10 cm (61.29%) and below 1 cm (25.81%). Huawei [11] forecasted positioning accuracy below 50 cm outdoor and below 1 cm indoor. Nokia [9] shared the view of reaching a centimetre level precision.

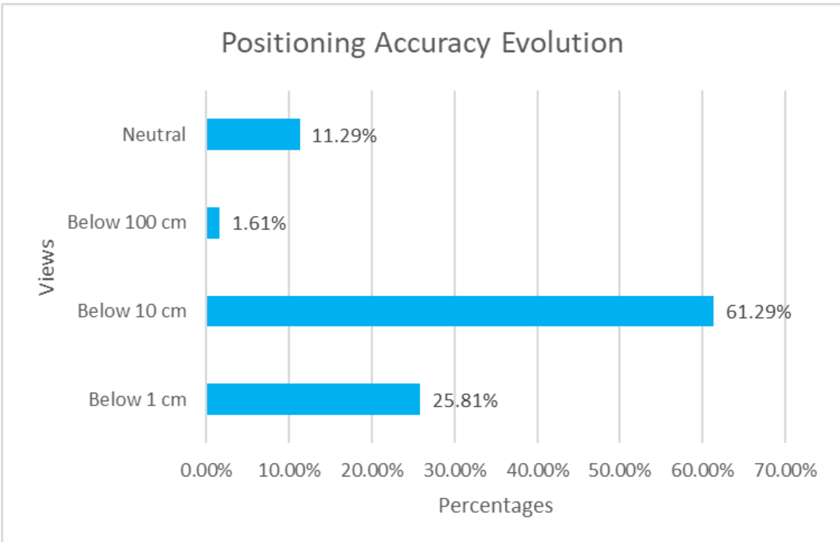

Figure 2-8 : Views on positioning accuracy evolution from EMPOWER consultation.

2.4 Summary and Conclusions

The 5G KPIs evolution trends towards 6G initially developed in our EMPOWER baseline roadmap have been proven to come in alignment with the views shared in the wireless research community. This is clearly evidenced through: i) the responses received in the EMPOWER consultation; and ii) emerging views on 6G recently shared by global players such as NTT DoCoMo, Ericsson, Nokia, and Huawei. A consensus seems to be emerging on the directions of travel and the ultimate KPIs to target in 6G. It will however take a few years before the industry converges officially on all target KPIs for IMT2030. This has only recently started at ITU-R with planning for work beyond IMT-2020 discussed at the ITU-R WP5D #35 meeting in February 2020. A first step that is being considered now by ITU-R is to develop an ITU-R Report on Future Technology Trends with a work scope and focus on providing a broad view of future technical aspects of terrestrial IMT systems considering the period up to 2030 and beyond, which will form the basis of the "Vision Beyond IMT-2020".

In the upcoming deliverable D2.4, we will provide a refinement of target KPIs with focus on those KPIs where we see clear target values emerging and receiving a wide consensus in the community.

3. Update on Wireless Technology Trends

This chapter presents emerging wireless technology trends, updated from the first EMPOWER trend report, D2.1 [3], including 3GPP and IEEE 802 standardization for the short-medium term trends, and selected technology trends for the long term. In the first technology roadmap, D2.2, from October 2019 [4], we presented quantified forecasts for 10 specific areas towards 2030, which was addressed in the following consultation. In this report, we take a more general view without quantification, but rather focus on broader technology areas.

3.1 Wireless technology trends for the short and medium terms

The key technology trends for the short-term evolution of 5G have been derived from the standardization outlook captured in two leading wireless standardization organizations, namely 3GPP and IEEE 802.11. In both organizations, we see a common trend to put priority on enhancing the various KPIs such as coverage, throughput, latency, reliability, energy efficiency, and positioning, to extend the support to emerging use cases such as i) V2X, ii) KPI-demanding industrial IoT, iii) private and dedicate networks, and iv) aerial and satellite networks [16][17][18]. Furthermore, we clearly see a trend to enhance the data collection and exposure from the network and devices to enable data-driven system optimization through artificial intelligence technologies, such as machine learning.

3.1.1 Technology trends in 3GPP Releases 17 and 18

Following the release of 3GPP 5G New Radio (NR) Release 15, the 3GPP is now gearing towards finalizing 5G NR Release 16 by Q2'2020. In parallel, there has been a few study items progressing with the aim to become agenda items for the future Release 17, that is being planned for the year 2020-2021. These study items include:

- Study on 6 GHz for LTE and NR in Licensed and Unlicensed Operations
- Study on NR beyond 52.6 GHz
- Study on solutions for NR to support NTN (Non-Terrestrial-Networks)
- Study on enhancement for disaggregated gNB
- Study on local NR positioning in NG-RAN

For Release-17 the physical layer work in RAN1 started at the beginning of 2020, whilst radio protocol and architecture work in RAN2 and RAN3, respectively, will start in the 2nd quarter. The timeline has been shifted 3 months for Release 16 and 17, and is now as shown in Figure 3-1.

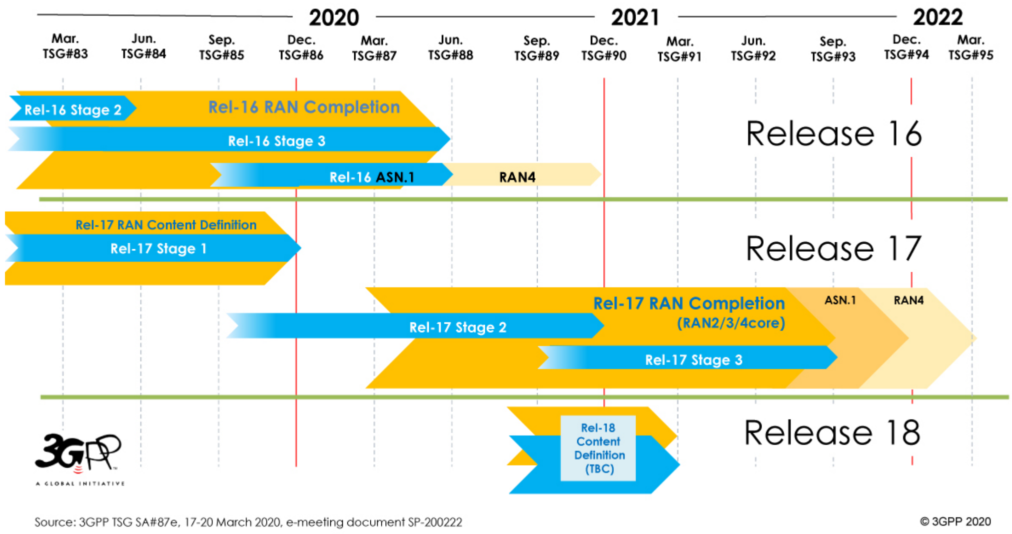

Figure 3-1: 3GPP RAN timeline for Release 16 to 18 [20].

Current 3GPP work plan from 25 March 2020 [19] contains enhancements related to a number of areas. Some highlights are summarized in the Table 3-1 below.

Table 3-1: 3GPP work plan highlights for Release 17 (2020-2021) [19].

Area	Short description
Use of 5G by different sectors ("verticals")	Asset Tracking, Critical Medical Applications (CMED), Cyber-physical control applications, 5G-LAN type services, Railway communications, 5G Location Services enhancements, Enhancements for UAVs. Factory/campus positioning, IoT, V2X positioning, 3D positioning, cm level accuracy, incl. latency and reliability improvements; NR-U positioning aspects; Idle and inactive
Satellite related	Architecture aspects and the integration of the satellite components and solutions for NR to support NTNs. Scoping of the normative WID. Include NTN-specific positioning
IoT related	Enhanced support for Industrial IoT (IIoT), including URLLC support for NR. Additional enhancements for NB-IoT and LTE-MTC, and NR small data transmissions
V2V and D2D related	Side-link enhancements and studies on NR side-link relay, and enhanced V2X services application support. Targeting maximum commonality between commercial, V2X, and Critical Communication usage of side-link while addressing their specific requirements. Targeting multi-cast/broadcast enhancements for V2X and Public Safety
NR enhancements	MIMO enhancements, dynamic spectrum sharing, power saving (NR-Lite), and Integrated Access and Backhaul (IAB). Targeting enhancements noticeably in power saving for optimal operation in mid-tier NR devices (e.g. wearables, surveillance cameras. Includes duplexing enhancement; Potentials for network coding; Mobile IAB. Enhancements for power saving of smartphones; Network power saving aspects as a separate sub-discussion

Other features	This includes support for mission critical services, multicast/broadcast and SON enhancements. Targeting extreme coverage requirements both indoor and outdoor, using relays. Includes SON and MDT; Data collection to enable AI is part of this discussion
NR new/ modified bands	NR band support from 52.6 GHz to 71 GHz. Targeting new waveform decision for spectrum above 52.6 GHz including 60GHz unlicensed Generic unlicensed operation enhancements not covered by any other item are addressed here;

The same work plan now also includes a few high level studies on Release 18 e.g. on IMS, the support of Railway Smart Station Services and so-called "Extra-territorial" 5G Systems. Whilst it is too early to define the scope of Release 18, a potential list of topics is attempted in Table 3-2 below, anticipating the Release 18 to include a mix of enhancements to Release 17 features plus a set of new features.

Table 3-2: 5G NR enhancements targeted in Release 18 (2021-2022).

No	Targeted NR enhancement	Short description
1	Drones	Enhancements to cover new scenarios, new requirements and KPIs for UAVs for both commercial and hobbyist applications.
2	NPN	Support new functionalities for closed access group (CAG) including cell selection, access control, intra-RAT and inter-RAT mobility, CU-DU functional split, and CP-UP split.
3	NR-WLAN DC Internetworking	NR/WLAN convergence at radio level in various deployment scenarios (e.g. MNO-deployed and enterprise-deployed).
4	Full Duplex	Support in-band full duplex for enabling simultaneous transmit and receive in the same time frequency resources.
5	1024 QAM	Introduction of very high order modulations up to 1024QAM primarily in FR1 and in downlink.
6	Synchronization	Support precise frequency, time and phase synchronization for NR communication and positioning based on NR reference signals.
7	Coverage	Operator-controlled sidelink coverage extension including relaying architectures, multiple hops, in both licensed and unlicensed spectrum.
8	Backhaul	Enabling NR based multi-hop backhaul including routing and bearer mapping functions for IAB nodes.
9	Mobility	Mobility enhancement for FR2 and for scenarios such as HSDN (high-speed dedicated network), Drones, and NTN.
10	Network Energy	Enhancement to the network energy efficiency through inter-RAT and inter-vendor energy saving cooperative schemes.
11	Diverse UE types	Enabling diverse UEs and designing techniques to reduce UE cost and complexity and to further improve UE energy efficiency.
12	QoE	Mechanisms to optimize collection of QoE measurements and KPIs, and the utilization of these measurements for enhanced resource allocation.
13	AI/ML	Enable AI/ML-based improvements in aspects such as MIMO, power control, beam management, mobility, energy saving, SON/MDT, etc.

3.1.2 Technology trends in IEEE 802.11

The IEEE 802.11 group has been actively specifying radio technologies in the key areas below [18]:

- 802.11ax – Highly Efficient WLAN for dense deployment and high throughput in 2.4, 5 and 6 GHz bands
- 802.11ay – Evolution of 802.11ad and support for higher than 20 Gbps throughput in 60 GHz band
- 802.11az – 2nd generation positioning features
- 802.11ba – Wake up radio for low power IoT applications
- 802.11bb – Light Communications
- 802.11bc – Enhanced Broadcast Services
- 802.11bd – Evolution of 802.11p for V2X
- 802.11be – Extremely High Throughput, higher than 30 Gbps, for operations between 1 and 7.25 GHz
- SENS SG – IEEE 802.11 Sensing Study Group

Whilst 802.11ax and 802.11ay are nearing completion (currently under Sponsor Ballot, expected completion during 2020), the 802.11 group continues to work on enhancements that push the performance envelope to new highs, such as the work underway in 802.11be targeting much higher throughput compared to 802.11ax. In addition, as the new use cases including many in local area networks demand additional capabilities to conventional throughput and latency, such as positioning and very low power, IEEE 802.11 has been working in parallel to improve these additional capabilities as clearly witnessed in the development of the 802.11az, .11ba, .11bb and .11bc. In addition, a new area of work has recently arisen, IEEE 802.11 based sensing. Below, we present a brief summary of the key technologies from 802.11ax, 802.11ay and 802.11be, as these are the most indicative on the technology trends aligning with and complementing 5G NR and its evolution in the upcoming 3GPP release 17 and beyond.

3.1.2.1 IEEE 802.11ax (Wi-Fi 6)

The IEEE 802.11ax, also known as Wi-Fi 6 (the sixth generation Wi-Fi), builds on the strengths of 802.11ac and aims to improve throughput performance of WLAN deployments in dense scenarios, with focus on 2.4, 5 and 6 GHz bands. The target set was at least 4 times improvement in the per-user throughput compared to 802.11ac. The key technologies which led to meeting the target set include:

- Orthogonal Frequency Division Multiple Access (OFDMA)-based radio resource allocation, with the added flexibility of resource unit dimensioning ranging from as small as 26 sub-carriers (2 MHz) to as large as 2 x 996 sub-carriers (160 MHz).
- Multi-user MIMO in both downlink and uplink for improved spatial multiplexing with support of up to 8 spatial streams delivering up to 4.8 Gbps at the physical layer.
- Denser modulation using 1024 Quadrature Amplitude Modulation (QAM), enabling a more-than-35-percent speed burst
- Higher spatial reuse through interference management enhancements in dense deployments including Overlapping Basic Service Set (OBSS) interference measurement, OBSS AP identification (colouring), OBSS packets detection, flexible Network Allocation Vector (NAV) setting, and Clear Channel Assessment (CCA) threshold control.

Flexible wake-up time scheduling enabling client devices to sleep much longer than with 802.11ac, and wake up to less contention, extending the battery life of the devices.

It is noteworthy that an evaluation has been carried out where it was demonstrated that 802.11ax meets or exceeds the MAC/PHY requirements for 5G Indoor Hotspot test Environment defined by ITU-R IMT-2020. A similar evaluation is also being conducted for the dense urban test environment. This clearly positions 802.11ax performance-wise and technology-wise on the 5G map despite the standard not being officially submitted to ITU-R IMT-2020 for ratification as an IMT-2020 (5G) system. This specification is close to completion, it is currently (end of March 2020) undergoing comment resolution of the sponsor ballot, which has an acceptance rate of 82%.

3.1.2.2 IEEE 802.11ay (millimetre wave – WiGiG)

IEEE 802.11ay aims to improve the throughput above 20 Gbps whilst remaining backwards compatible with its predecessor 802.11ad in the 60 GHz band. The key technologies which led to meeting the target set include:

- Highly efficient beam search and beam tracking protocols, and analogue/digital hybrid beamforming capability
- Single-user MIMO and multi-user MIMO in the downlink, with up to 8 spatial streams, including changes to the beamforming protocol and exploiting antenna polarization.
- Channel bonding and aggregation up to 4 bonded channels (8.64 GHz channel) either adjacent (bonding) or non-adjacent (aggregation).
- Non-uniform constellation modulation with constellation orders up to 256QAM
- Advanced power saving features

As 802.11ay targets the 60 GHz band, it therefore aligns more with the evolution of 5G NR anticipated in 3GPP Release 17 where the high frequency band (FR2) extends beyond 52.6 GHz, and this for both licensed and unlicensed spectrum. This specification is close to completion, it is currently (end of March 2020) undergoing comment resolution of the sponsor ballot, which has an acceptance rate of 89%.

3.1.2.3 IEEE 802.11be (extreme high throughput)

The IEEE 802.11be targets extreme high throughput (30 Gbps or higher) as well as high reliability and very low latency compared to 802.11ax whilst operating in the 2.4, 5 and 6 GHz bands. The work has recently started with a targeted completion date around 2024. The key technologies being considered towards meeting the targeted performance include:

- 320MHz bandwidth and more efficient utilization of non-contiguous spectrum
- Multi-band/multi-channel (or multi-link, in general) aggregation and operation
- 16 spatial streams and MIMO protocols enhancements
- Multi-AP Coordination (e.g. coordinated and joint transmission)
- Enhanced link adaptation and retransmission protocol (e.g. HARQ)
- Adaptation to regulatory rules specific to 6 GHz spectrum

This specification work is currently ongoing with multiple parallel meetings on the different MAC and PHY aspects of the project. The Standard Features Document (SFD) has already been created and it is populated with the new features that the members are agreeing on.

3.1.2.4 IEEE 802.11az (Next generation positioning)

IEEE 802.11az project is the evolutionary roadmap of accurate 802.11 location (FTM) appearing first in previous revisions of the 802.11 standard, which is based on triangulation of access points.

New features IEEE 802.11az aims at tackling are:

- Accurate indoor Navigation (sub 1m and into the <0.1m domain).
- Secured (authenticated and private) positioning – open my car with my smartphone, position aware services (money withdrawal).
- Open my computer with my phone/watch.
- Location based link adaptation for home usages (connect to best AP).
- Navigate in extremely dense environments (stadia/airport scenarios).

In order to achieve the above use cases, this specification focuses on the following enhancements to the IEEE 802.11 base line:

- Medium efficient operation via dynamic (demand dependent) measurement rate.

- Adaptation to next generation mainstream 802.11ax Trigger Based Operation (MIMO, Trigger Frame, NDP frame)
- Authenticity and privacy and anti-spoofing mechanism via PMF in the unassociated mode and PHY level randomized measurement sequences (HE LTF sequences protection).
- Improved accuracy via MIMO and larger BW available in the <7 GHz band for 11ax.
- MIMO enablement for measurement for improved accuracy especially for NLOS or NNLOS conditions.
- Passive location with fixed overhead independent of number of users.

3.1.2.5 SENS SG – IEEE 802.11 Sensing Study Group

The SENS SG is a recently created Study Group focused on developing a PAR (Project Authorization Request) to create a Working Group in the area of IEEE 802.11-based sensing. Currently the SG line of thought lies in the line of enhancing WLAN sensing operation beyond the channel estimation capabilities offered by IEEE 802.11 by defining modifications to the MAC and PHY that enhance wireless sensing operation in license-exempt frequency bands between 1 GHz and 7.125 GHz and above 45 GHz. In April 2020, the IEEE 802.11 WG has performed an e-Ballot for approval of the CSD and PAR of the upcoming TG on Sensing. Both ballots passed, therefore a new Task Group will be created to standardize solutions related to this topic.

3.1.3 Technology trends in IEEE 802.15

As compared to IEEE 802.11, which is focused on wireless local area network (WLAN), IEEE 802.15 is rather focused on wireless personal area network (WPAN). There are several standards defined in IEEE 802.15 such as, 15.3 on high-rate WPAN, 15.4 on low-rate WPAN, and 15.7 on visible light communications. Of interest to the 5G evolution is the 15.3d, especially as this is the world's first wireless communication standard targeting operations in the bands above 100 GHz, which is commonly envisioned to be the next targeted spectrum on the roadmap of 5G evolution for the longer term. The IEEE 802.15.3d standard targets nominal PHY data rate of 100 Gbps in the bands 252 to 325 GHz, at ranges as short as a few centimetres and up to several 100m. The IEEE 802.15.3d technologies:

- 8 different channel bandwidths (as multiples of 2.16 GHz)
- Two PHY modes, THz-Single Carrier, and THz-On-Off-Keying
- MAC based on IEEE 802.15.3e-2017 including the concept of "Pairnet" for point-to-point highly directive interference-free access
- Constellation modulation up to 64-QAM order
- LDPC and Reed-Solomon forward-error-correction codes

The standard was published in 2018 but the work continues in an IEEE 802.15 Interest Group THz targeting future enhancements and extended operations towards 3000 GHz spectrum.

The THz IG has been meeting intermittently during the last years, being the last meeting on the IEEE Plenary meeting held on July 2019 (Vienna). Due to the COVID pandemic, the group has not yet scheduled any meeting in 2020. The latest contributions, at the time of writing this document, on the THz IG relate to channel characterization between 60 and 300 GHz, simulation of performance for backhaul links operating at 300 GHz and demonstrations of links operating at 100GHz.

3.2 Wireless technology trends for the longer term

The key technology trends for the longer-term evolution of 5G in the timeframe 2025-2030 have been derived from the 6G research agendas set by international research forums listed in section 1.1. The direction of travel set in these more visionary forums is steered towards disruptive technologies which maturity for standardization and commercial use is difficult to predict soon, making these technologies exciting for fundamental research much desired by the academic and research community [21]-[35]. These technologies target the KPIs outlined previously in section 2.1 and section 2.2, which are also speculative and derived more from the ambition to: i) achieve much higher performance in every current KPI dimension, and ii) add new capabilities by redefining some current KPI dimensions or adding new KPI dimensions to the design space.

The emerging vision of 6G is a transformation of today's 5G system from being the backbone of everything connected towards becoming the backbone of every smart thing connected. It is a revolution from the mobile internet of everything to the mobile intelligence of everything. The sixth of 6G is also often used to convey the vision along the lines of 6G adding a sixth sense to today's 5G.

Towards this vision, we have identified five technology areas anticipated to impact 6G, namely i) circuits and devices, ii) radio transceivers, iii) radio access system, iv) network protocols, and v) data and intelligence. The trends in these areas are briefly outlined below:

1) **Circuits and devices** trending at nanometres level with node scaling targets of Power-Performance-Area-Cost (PPAC) breaking through the limits of Moore's Law.
2) **Radio transceivers** supporting extreme requirements at Tbps data rates, sub-ms latency, and sub-mWatts power.
3) **Radio system** expanding to integrate (un)licensed, (non)terrestrial, and (non)communications sub-systems, in a 3-D space with fluid topologies.
4) **Network protocols** catering for the requirements of next generation internet including determinism, time-sensitivity, and automation.
5) **Data** (small and big) driving E2E system (network, device and application) optimization with pervasive collaborative **intelligence** distributed across terminals, edge, fog and cloud.

In the following sub-sections, we briefly present a selection of advanced wireless research topics emerging on the roadmap towards 6G and beyond. We anticipate that research and evolution within these topics are representing enablers for the trends in the above areas.

3.2.1 Above 100 GHz communications

Frequencies above 100 GHz are being explored for 6G as a natural extension of the current frequency limit of 100 GHz set in 5G. Whilst there is already a published standard (IEEE 802.15.3d) operating at bands above 100 GHz, 802.15.3d is limited to point-to-point communication scenarios, and the practical implementation and commercialization are at least a decade away due to the tremendous challenges for creating cost-effective transceivers at these frequencies. These challenges range from hardware and circuits to antenna arrays, baseband processing at above 100 Gbps data rates, channel access, multiplexing and networking protocols.

Over the next decade, it is believed that advances in devices, circuits, software, signal processing, and systems will make sub-THz and THz communications a commercial reality. Beyond communications, these frequencies offer additional capabilities such as sensing, radar, imaging, and ultra-accurate positioning, which is promising a new paradigm of integrated sensing and communication in the same frequency bands. The research community is quite active in addressing the various research challenges in the frequency ranges up to 3 THz. This is clearly evidenced in the THz cluster in EC H2020, the DARPA T-MUSIC programme, and the IEEE 802.15 THz interest group. The FCC in the US recently announced in 2019 giving Spectrum Horizon experimental licenses for spectrum between 95 GHz and 3 THz, which makes a total of 21.2 GHz of spectrum between 116 and 246 GHz available for unlicensed devices.

3.2.2 Metamaterials-based intelligent surfaces

Metamaterials (meta- from Greek meaning "after" or "beyond") are synthetic composites with structures and properties not found in natural materials. In wireless communications, metamaterials are envisioned for the design of new classes of antenna arrays called meta-surfaces bringing the capability to shape the radio waves according to the generalized Snell's laws of reflection and refraction.

Meta-surfaces have a wide range of applications in various frequency bands up to THz frequencies including: i) programmable "intelligent" surfaces, ii) miniaturized cavity resonators, iii) absorbers, iv) biomedical devices, and v) terahertz switches. By embedding programmable "Intelligent Reflecting Surfaces" (IRS) surfaces into the environment (e.g. on walls, street furniture, etc.), such as frequency-selective surfaces, smart reflect-arrays or mirrors, or arrays of low-cost antennas, one may be able to change the characteristics of the wireless environment and thus optimize its operation accordingly. This is akin to adding a new degree of freedom in the wireless system design where now the environment is controllable and programmable thanks to these meta-surfaces.

Furthermore, in addition to altering the propagation environment, programmable meta-surfaces are anticipated to radically change the design of wireless transceivers by enabling the programmability of transceiver components such as phase, amplitude, frequency and even orbital angular momentum (OAM) of an electromagnetic (EM) wave, effectively enabling the modulation of a radio signal without a mixer and RF chain.

3.2.3 Massive Low Earth Orbit Satellites and High-Altitude Platforms

Low Earth Orbit (LEO) satellites orbit between 400 and 2000 km above the Earth's surface. Today, there are some hundreds of these satellites providing a blanket coverage and connectivity everywhere on Earth. Over the next decade, it is anticipated that the cost of building and launching LEO satellites will decrease significantly and advances in manufacturing, robotics, energy, and artificial intelligence will significantly enhance their capabilities. LEO satellites are therefore envisioned to be massively deployed over the next decade making them a co-primary infrastructure to consider from the outset in the design of 6G.

Since May 2019, SpaceX' system 'Starlink' has launched more than 300 satellites, planning for almost 12000 before 2027 [29]. There are two other main proponents, Amazon's Kuiper project planning more than 3000 satellites, and OneWeb planning 650 satellites. OneWeb has launched 74 satellites since February 2019 [30]. Regulatory agreements were reached for LEOs and MEOs at the ITU R WRC-19 (see section 4.2).

High-Altitude Platforms (HAPs) are designed to fill in the gaps between LEO satellites and ground base stations. They include passive balloons and highly advanced drones with wingspans larger than 20 meters. These are deployed today to provide connectivity services to disaster zones and remote areas of the planet, as well as creating Persistent Surveillance Systems that can monitor and police entire cities in real time. Over the next decade, HAPs are anticipated to be deployed more widely and in higher density and enhanced by advances in manufacturing, drones, energy, and artificial intelligence. HAPs are therefore positioned to become a key infrastructure element in the architecture and deployment of future 6G. Global and regionally harmonized designations for HAPS at ITU-R WRC-19 will most likely facilitate the development of HAPS services and allow trials to move towards commercial deployments (see also section 4.2).

3.2.4 Wireless power transfer and Energy harvesting

Wireless power transfer (WPT) and energy harvesting including scavenging from ambient RF signals are expected to accelerate and mature in time for 6G. This is because i) the envisioned communication distance in 6G will become much shorter, ii) the network density will be much greater, including densification by means of battery-powered moving and flying base stations, and iii) various terminal devices will be more power hungry than ever because of the huge computation demands for on-device AI processing. Currently, we know WPT as used for backscatter communication technologies, such as NFC used in different smart cards and mobile phones. These require extremely short distances. An interesting scenario is also to use an "Energy Node" (EN) to supply surrounding devices with sufficient power to be able to transmit messages to a nearby access point.

3.2.5 Artificial Intelligence

Artificial Intelligence (AI) is widely tipped to be a major disrupting technology that will impact the design of beyond 5G and 6G. Today researchers have demonstrated numerous examples of applying successfully AI in wireless communications, from physical layer design such as channel coding, channel estimation, and MIMO precoding, to radio resource management and mobility management, and to network management and orchestration. In addition to the big data-driven centralized approach today, we will see more of a small data-driven distributed approach in 6G. The AI services will be ubiquitous, from the core to the end devices in the network. To satisfy increasingly stricter latency requirements, more intelligence will be pushed towards the edge of the networks.

Federated learning and transfer learning are two important machine learning approaches that makes this possible. Federated learning, or collaborative learning, makes it possible to trains an algorithm across multiple decentralized edge devices or servers holding local data samples. No data are exchanged in this process, only the ML model. Hence, federated learning i) alleviate the issues of collecting big data to train the models in centralized data centres, ii) integrate seamlessly all the data and intelligence that is pervasively distributed across the continuum from the terminal all the way up to the Cloud, and iii) mitigate data privacy and reduce network latency. Federated AI is expected to benefit from significant advancement in the fields of artificial narrow intelligence, artificial general intelligence, distributed computing, neural processing units and sensor technology.

Transfer learning makes it easier to train a ML model by taking an already trained ML model for a similar problem as the starting point. This gives huge savings in the time it takes to generate ML models, improves the performance and requires less data for the learning. With a good library of pre-trained ML models it will be possible for communications engineers to use ML much more widely throughout the network than today. As a result of this, almost every object in the network will be data driven.

3.2.6 Quantum communication

Quantum communication is envisioned as a disrupting technology that will help 6G (and beyond) achieve its targets of Tbps throughput, ultra-low latency and ultra-high security. In addition to its inherent security feature of quantum entanglement which cannot be accessed without tampering, quantum communication is particularly suitable for long distance communication, which made satellites and HAPs as obvious trusted nodes in the architecture of quantum key distribution and regeneration. Initial quantum devices have also been realized recently using single photon emitters operating at few degrees above the absolute zero temperature. A complete quantum computing architecture has recently been demonstrated [31]. The next decade is promising significant advancements to quantum devices so they can operate at normal temperatures.

3.2.7 Cell-free massive MIMO networks

Cell-free MIMO is a new name for network MIMO and distributed MIMO. The network is user-centric, meaning that each user is connected to a user specific subset of Access Points (APs) that cooperate to jointly serve the user. The APs are connected via front-haul connections to Central Processing Units (CPUs) that coordinates transmissions from APs phase-coherently, and the CPUs are inter-connected via backhaul connections. Time Division Duplexing (TDD) is used to ensure scalability in massive MIMO systems, which means that channel estimation and precoding are performed by each AP and therefore no instantaneous channel state information has to be sent over the fronthaul.

The term "cell-free" refers to the fact that the network appears to be without any cell boundaries during data downlink transmissions, at least from a user perspective. The data detection on the uplink can be performed at each AP, at the CPU or the detection can be split between the AP and the CPU. The network might not be cell-free for control signals as AP specific synchronization and reference signals might be used. The cell-free massive MIMO technology is very attractive for removing inter-cell interference, which is a major bottleneck in dense networks.

Theoretical studies have shown that cell-free massive MIMO networks can achieve significantly better performance than conventional small cell networks. For example, in [36] it is found that the throughput can be increased by a factor of five under uncorrelated fading conditions, and with a factor of 10 when shadow fading is correlated.

One of the main challenges for implementing cell-free massive MIMO networks are to have cost efficient deployments while achieving sufficiently accurate network synchronization and satisfying the requirements for the fronthaul and backhaul connections.

3.3 Summary and Conclusions

We observe that there is high activity on research, development and standardization on a diverse set of technologies towards 6G. In standardization, the two big players, 3GPP and IEEE are both playing major roles. Short and medium term, the 3GPP is concentrating on the evolution of 5G, while the IEEE 802.11 group is both working towards extreme throughput as well as positioning and sensing

On the technology trend side, we started out to identify five major areas, which we believe are central to the enablement of 6G. Further, we have chosen to describe the outlook for a number of topics, which will be components on tomorrow's communication networks and systems. Future systems will have to make use of new technologies as well as new resources and methods to fulfil the expected demands, as we have seen in the roadmap consultation. New resources include both spectrum beyond 100 GHz as well as integrating LEOs and HAPs. New technologies include metamaterials, wireless power transfer (WPT) and quantum communications, while the use of AI will be ubiquitous throughout the networks and platforms.

4. Wireless Regulatory Trends

Wireless communication is one of the largest growing industries globally. The wireless data rate is a doubling every 18 months. The latest Ericsson Mobility Report [37] forecasts 160 EB (Exabytes) global monthly traffic in 2025. A major increase in available data speeds is also foreseen. The latest Cisco Annual Internet Report [39] forecasts that both mobile and Wi-Fi speeds from mobile devices will triple between 2018 and 2023. It is also expected that 5G speeds will be 13x higher than the average mobile connection by 2023.

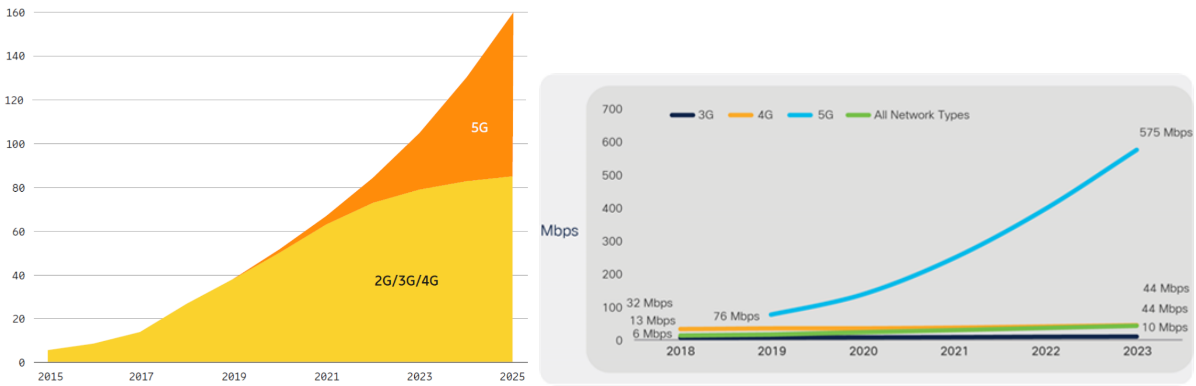

Figure 4-1: Ericsson Mobility Report [37] (left) mobile data traffic forecasts,
and Cisco Annual Internet Report [39] (right) mobile speed forecasts.

Another trend is the increase in so-called offload traffic, i.e. traffic from mobile devices not carried by the cellular networks, but by broadband and Wi-Fi access points. The Cisco Visual Networking Index from 2019 [38] forecasts that in 2022, 41 % of the traffic from mobile devices will be carried over non-cellular networks. Additionally, even the capacity of 4G and 5G cellular systems have increased, the percentage of Wi-Fi offload is expected to increase when moving to 5G:

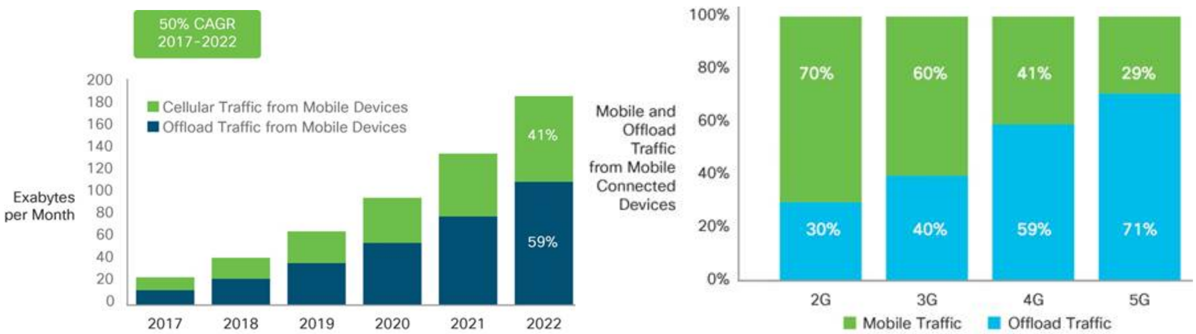

Figure 4-2: Cisco VNI forecast of so-called offload traffic from cellular to other wireless networks, typically Wi-Fi [38].

Further, a high growth in Wi-Fi usage is expected. Cisco predicts a Compound Annual Growth rate (CAGR) of 30% in public Wi-Fi hotspots from 2018 to 2023 [39]. Of these, 66.8% of the endpoints will be equipped with 802.11ac (Wi-Fi 5), and 27.4% will be equipped with 802.11ax (Wi-Fi 6) in 2023.

An important trend is the expected growth in M2M connections and devices. In mobile M2M connections are expected to reach 4.4 billion connections in 2023, with an annual growth of 30%, this is almost four-fold from 2018. This is the fastest growing connection category foreseen, followed by “phablets” with an annual growth of

13%. The number of mobile M2M connection will almost reach the same as smartphones in 2023. In addition, the traffic over M2M connections will grow even faster, because of increased deployment of video applications and the increased use of telemedicine and smart car navigation systems requiring both greater bandwidth and lower latency.

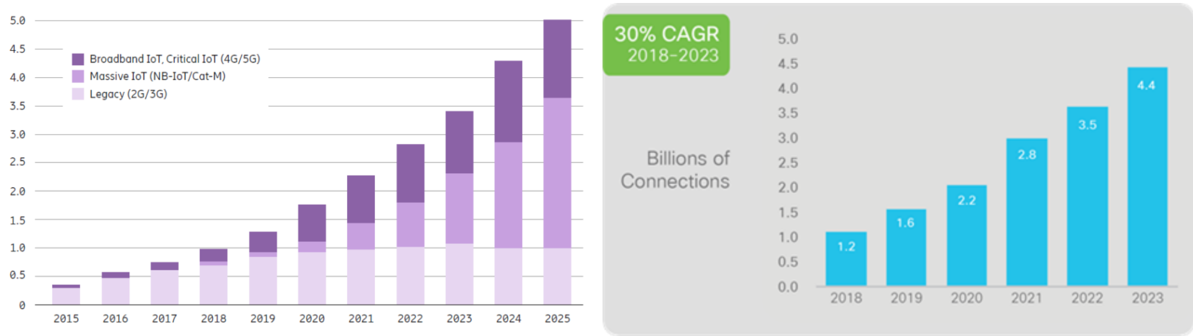

Figure 4-3: Ericsson Mobility Report forecast on Cellular IoT (C-IoT) towards 2025 [37] (left), and Cisco forecast on mobile M2M connections towards 2023 [39].

Wireless communications need spectrum and the forecasts above illustrates very well the high pressure for increasing the available spectrum, especially for cellular services, by ITU-R denoted IMT (International Mobile Telecommunications). Even if the cellular and wireless radio access technologies are being improved to increase the spectrum efficiency and utilization, one of the most important factors to provide the requested capacity increase is freeing more spectrum for wireless and mobile.

The "ICT Regulatory Tracker"[1] [40] from ITU is an interactive tool to help decision-makers and regulators more fully understand the changing terrain of ICT regulations. ICT regulations have been classified in "generations", from G1 (the first) where regulated public monopolies taking a "command and control" approach, up to G5 (not to be confused with the ITS G5 communications standard), where different regulatory agencies are collaborating with the stakeholders to form a harmonized approach across sectors now dependent on ICTs.

4.1 Actors and stakeholders

In this trend report, we have looked at what some of the major stakeholders in the EU-US dimension regard as important wireless regulatory trends. We have chosen to limit the analysis to spectrum issues, omitting other wireless regulatory issues.

Our main sources have been the spectrum organizations in Table 1-3, and the following organizations and groups:

- **Networld2020 ETP Vision Group [2]:** NetWorld2020 is the European Technology Platform for communications networks and services. It gathers players of the communications networks sector, including industry leaders, SMEs, and academic institutions.
- **GSM Association (GSMA)[3]:** The GSMA represents the interests of mobile operators worldwide, uniting more than 750 operators with almost 400 companies in the broader mobile ecosystem, including handset and device makers, software companies, equipment providers and internet companies, as well as organizations in adjacent industry sectors.
- **5G-IA Spectrum Working Group[4]:** Promote research results in the spectrum area obtained by 5G PPP/H2020 projects as well as relevant FP7 projects. Establish a knowledge base from European and

[1] https://www.itu.int/net4/itu-d/irt/#/

[2] https://www.networld2020.eu/

[3] https://www.gsma.com/

[4] https://5g-ia.eu/about/5g-ia-work-groups/

other Global project results concerning advances in spectrum research. Liaise with spectrum groups or entities in regulatory bodies and industry associations.

4.2 Highlights and key outcomes of ITU-R WRC-19

The World Radiocommunication Conference 2019 (WRC-19) was held in Sharm El-Sheikh, Egypt, from 28 October to 22 November 2019 [41]. Key topics that were discussed and relevant for EMPOWER are mentioned below.

New frequency bands for IMT-2020 were identified in the mm-wave range giving a total of 17.25 GHz new bandwidth (24.25-27.5 GHz, 37-43.5 GHz, 45.5-47 GHz, 47.2-48.2 GHz and 66-71 GHz). [42]. 85%, or 14.75 GHz was actually harmonized worldwide. These bands are extremely important to support the 5G evolution and B5G for both high bandwidth and new services (industry, healthcare, education etc.), and also meeting tough latency and reliability demands (URLLC-services). An important challenge for all frequency regulations is to ensure co-existence and interference control towards other services. In this case, the gaps in between is a.o. to protect sensitive science services, like the Earth exploration satellite service (EESS).

Non-geo-stationary satellite orbit (non-GSO) systems, means in our context the new LEO and MEO systems being planned and launched (see section 3.2.3). Operators are now required to deploy within certain time limits after the end of the current regulatory period (10% after two years, 50% after 5 years and 100% after 7 years). This might be an important pressure to ensure that systems are actually put in operation.

A number of frequency bands in the mm-wave range for use by High altitude platform station (HAPS) systems were identified, including bands already allocated for fixed services (31-31.3 GHz, 38-39.5 GHz, 47.2-47.5 GHz and 47.9-48.2 GHz). In region 2 (Europe), additional bands were agreed (21.4-22 GHz and 24.25-27.5 GHz) [42].

The sharing study for the band 275-450 GHz resulted in that a number of sub-bands were added to the frequency allocation table (FAT) (275-296 GHz, 306-313 GHz, 318-333 GHz and 356-450 GHz). There will be continued studies on sharing and protection of EESS.

Finally, new agenda items for WRC-23 were identified, of which two seems most relevant in this context:

- Agenda Item 1.2: Further new bands for IMT between 3 and 4 GHz, in the 6 GHz, 7 GHz and 10 GHz bands, based on sharing studies.
- Agenda Item 1.4: Use of HAPS as IMT base stations (HIBS) in certain bands below 2.7 GHz already identified for IMT.

Both these items are relevant in the evaluation of progress and opportunities towards 6G. Further, early work towards WRC-27 was identified. As we have already identified in section 3.2.1, high frequencies are potentially very handy, among others, for accurate positioning. A resolution to study sharing compatibility and new allocations to “Radio Location Services” (RLS) in the range 275-700 GHz, and to study sharing and compatibility between 231.5 and 275 GHz for active mm-wave and sub-mm-wave imaging applications, was agreed.

4.3 Trends in Unlicensed spectrum

Offloading cellular networks is mainly done using Wi-Fi systems, which utilize unlicensed spectrum, for both private (home routers) and enterprise network solutions. The band between 5.150 and 5.925 GHz is today shared between several services, where Wi-Fi is being used to provide mobile services. Sub-bands are shared with certain radar types, and the upper 70 MHz is allocated for ITS (Intelligent Transport Systems) in some markets. Further regulations was discussed at WRC-19 [42] without any clear recommendations except to go for global or regional harmonization.

Using 3GPP technologies (LTE and 5G NR) in unlicensed bands, primarily 5.2/5.8 GHz, is being worked on. The motivation is the need for capacity offloading which is dominated by Wi-Fi technology. However, to integrate use of unlicensed spectrum more tightly into the cellular networks, using LTE and 5G NR in unlicensed bands has been standardized since Release 13 and is closely linked to studies and features for dynamic spectrum sharing (DSS). Table 4-1 shows the evolution of 3GPP technologies and usage of unlicensed spectrum. It is expected that 3GPP will address the higher frequency unlicensed spectrum (e.g. 60GHz band) in future releases (rel 17).

Table 4-1: 3GPP unlicensed roadmap

Technology	Release	Short description
LTE-A	Release 10-11	• Core Network based WLAN offload
	Release 12	• RAN-assisted interworking between LTE and WLAN • LTE-U – based on R12. Proprietary
LTE-A Pro	Release 13	• RAN Controlled LTE-WLAN Interworking (RCLWI), LTE/WLAN Radio Level Integration with IPsec Tunnel. (LWIP), LTE-WLAN Aggregation (LWA) • License Assisted Access (LAA)
	Release 14	• eLAA • 5G SI including requirements on unlicensed
5G NR	Release 15	• 5G Phase 1 WI (licensed only) • 5G SI on NR for unlicensed
	Release 16	• 5G Phase 2 WI (full system) • 5G WI on NR for unlicensed (NR-U) • NR-U for 5 and 6 GHz bands • Asynchronized and synchronized operations • Listen Before Talk (LBT)
	Release 17	• Generic enhancements to NR-U • 5G SI on Dynamic Spectrum Sharing (DSS)

4.4 Trends in Spectrum sharing

As discussed in the chapter introduction, allocated spectrum is one of the main factors that determine the system capacity. The Networld2020 ETP is discussing spectrum sharing and reutilization in their Vision Paper [21]. Spectrum sharing can be applied both to licensed as well as unlicensed spectrums. Cellular systems are usually deployed with common inter-RAT (Radio Access Technology) radio resource management, however joint utilization of licensed and unlicensed spectrum will require adaptive strategies such as cognitive radio concepts.

Different types of shared access can be achieved in the frequency, spatial and temporal domains:

- In frequency with individual licenses for each channel.
- In geography with licenses either including specific geographical areas or specifying the location of transmitters.
- In time where the licenses have a fixed and relatively short duration.

The borderline between exclusive licensing versus licence-exempt use of spectrum is gradually becoming diluted by the appearance of new spectrum regulation schemes based on various forms of organized spectrum sharing. Some examples of such schemes are:

- Light licensing
- Authorized Shared Access (ASA)/Licensed Shared Access (LSA)
- Pluralistic licensing (PL)
- Citizens Broadband Radio Service (CBRS)

4.4.1 Light licensing

There is no formal definition of light licensing, and it has slightly different meaning for different people.

In ECC Report 80 [47] light licensing is described in the following way:

> *"A 'light licensing regime' is a combination of licence-exempt use and protection of users of spectrum. This model has a "first come first served" feature where the user notifies the regulator with the position*

and characteristics of the stations. The database of installed stations containing appropriate technical parameters (location, frequency, power, antenna etc.) is publicly available and should thus be consulted before installing new stations. If the transmitter can be installed without affecting stations already registered (i.e. not exceeding a pre-defined interference criteria), the new station can be recorded in the database. A mechanism remains necessary to enable a new entrant to challenge whether a station already recorded is really used or not. New entrants should be able to find an agreement with existing users in case interference criteria are exceeded."

In this definition, it is up to a new user of the spectrum to verify that a new transmitter station does not interfere with stations already in the database.

Ofcom, on the other hand, describes light licensing in the following way in [48]:

"Light-licensing is a mechanism whereby the users of a band are awarded non-exclusive licences which are typically available to all, and are either free or only have a nominal fee attached to them. There may be further obligations associated with the provision of a licence such as the need to register the location of any transmitters and possibly to coordinate their deployment with other registered users."

In this definition users are awarded non-exclusive licences, and it is up to the entity awarding the license to perform the necessary frequency planning to ensure that the new transmitter do not interfere with existing transmitters or oblige the user to coordinate their deployment with other registered users

In any case, light licensing usually permits higher power than licence-exempt regimes.

4.4.2 Authorized Shared Access/Licensed Spectrum Access

Licensed Shared Access (LSA) is a voluntary sharing method where an incumbent can share spectrum with another user, typically on a commercial basis. LSA makes it possible to dynamically share a frequency band, whenever and wherever it is unused by the incumbent users. Shared use of the spectrum is only allowed on the basis of an individual authorisation (i.e. a license).

LSA is a further development of an industry proposal for Authorised Shared Access (ASA). ASA was introduced to enable access to additional frequency bands for mobile broadband which were identified for IMT but not available in some countries. The concept was extended as Licensed Shared Access (LSA), with the potential for application to other services in addition to mobile broadband.

LSA is defined by RSPG in [46] as:

"*A regulatory approach aiming to facilitate the introduction of radiocommunication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the Licensed Shared Access (LSA) approach, the additional users are authorised to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorised users, including incumbents, to provide a certain Quality of Service (QoS)*".

4.4.3 Pluralistic licensing

In [50] Pluralistic Licensing (PL) is described as:

"*The award of licenses under the assumption that opportunistic secondary spectrum access will be allowed, and that interference may be caused to the primary with parameters and rules that are known to the primary at the point of obtaining the license*".

The main idea behind pluralistic licensing is to use financial and other means to leverage better spectrum usage [50]. When a primary user is "buying" spectrum, he can select from different types of possible licenses. The licenses differ in how much and what type of interference the primary must accept from secondary users of the spectrum; where accepting higher interference means a lower price. That is, the primary will choose from a range of offered "pluralistic licenses" each with associated fees, and each specifying alternative opportunistic secondary spectrum access rules with known interference characteristics.

Whereas LSA requires that secondary users obtain a license, the idea in PL is that no license is required for the secondary. Hence, PL is simpler and quicker way to implement spectrum sharing than LSA, particularly for the secondary users.

PL encourages design of primary systems that are more robust and able to tolerate higher levels of interference, e.g. better rejection of adjacent channel interference, better robustness to short-lived interference and better sensitivity. This will both reduce cost for mobile operators and other primary system owners and generally increase the utilization of spectrum resources. PL might also lead to better design of secondary systems, e.g. better sensing for secondary-secondary awareness (i.e. better secondary coexistence).

4.4.4 The Citizens Broadband Radio Service (CBRS)

The CBRS band is 150 MHz of spectrum made available for commercial broadband use on a shared basis with the federal government which currently operates mission-critical radiolocation services in this spectrum. Commercial users of the 3.5 GHz CBRS band will share this spectrum with existing incumbents, including the federal government. Access and operations is managed by a dynamic spectrum access system. Wireless carriers using CBRS might be able to deploy mobile networks without having to acquire spectrum licenses.

CBRS has a three-tier architecture for sharing the spectrum from 3550 MHz to 3700 MHz:

- **Incumbent Access:** Incumbent Access users include authorized federal and grandfathered Fixed Satellite Service users currently operating in the 3.5 GHz Band and in particular U.S. Navy radar operators. These users are protected from harmful interference from Priority Access and General Authorized Access users.
- **Priority Access**: The Priority Access tier consists of Priority Access Licenses (PALs) that are assigned using competitive bidding within the 3550-3650 MHz portion of the band. Each PAL is defined as a non-renewable authorization to use a 10 MHz channel in a single census tract for three-years. Up to seven total PALs may be assigned in any given census tract with up to four PALs going to any single applicant. Applicants may acquire up to two-consecutive PAL terms in any given license area during the first auction.
- **General Authorized Access:** The General Authorized Access tier is licensed-by-rule to permit open, flexible access to the band for the widest possible group of potential users. General Authorized Access users are permitted to use any portion of the 3550-3700 MHz band not assigned to a higher tier user and may also operate opportunistically on unused Priority Access channels.

4.4.5 Conclusions and Perspectives

It is a fact that the demand for spectrum is growing both due to introduction of new services and application and that existing applications tend to require increasing bitrates. Since the amount of spectrum available is finite, it will be necessary to utilize the spectrum more efficiently. At the same time, greater and more intense spectrum sharing is becoming possible because of more sophisticated technology and new authorisation approaches. Hence, the trend will be towards more spectrum sharing in the future.

As no single spectrum sharing regime satisfy all requirements, different sharing regimes will be used ranging from exclusive licenses to purely license-exempt usage. It should be expected that spectrum sharing will be the norm, and that exclusive licenses will be used only when strictly necessary.

It is uncertain to what degree regulators will promote self-control by the markets. Some people believe that we will see a gradual change from ex ante regulation (i.e. strict regulation and controlling beforehand) to ex post regulation (i.e. letting market forces work and only intervening in cases of reported problems).

As the use of spectrum sharing will increase, regulators must spend more resources on controlling that users comply with the sharing rules. This calls for an extensive deployment and automation of radio monitoring equipment, including "cloud" monitoring by dispersed nodes. Regulators role as agents for consumer protection will increase, including verification of the quality of public wireless services delivered to end-users and general impartial market supervision.

The effectiveness of spectrum sharing is improving as more sophisticated sharing technologies are developed and new authorization approaches are introduced. The trend is towards more spectrum sharing, especially in higher frequency bands such as the millimetre wave frequencies where shorter range and narrow antenna beams make it easier to control interference. It is not unlikely that spectrum sharing becomes the default in these bands.

4.5 Trends in high frequency spectrum

Current wireless systems operate mostly in the so-called UHF band (300 – 3000 MHz). 5G has already targeted higher bands, initially 3.6 GHz and 26/28 GHz in order to provide sufficient bandwidths. In this context, we look at frequencies from 26 GHz and above and we divide into so-called millimetre-wave (mm-wave) frequencies (30 – 300 GHz) and THz frequencies (100 GHz – 10 THz).

The interest for using mm-wave frequencies is increasing, and several bands up to 86 GHz were identified for IMT at WRC-15. Sharing studies has been performed and was discussed at WRC-19 as explained in section 4.2. For non-cellular use, the 60 GHz unlicensed band is already being used for short range wireless systems, like the IEEE 802.11ad and IEEE 802.11ay ("WiGig") between 57 and 70 GHz.

Further for sub-THz frequencies, the band from 275 to 450 GHz was discussed at WRC-19 to be used for land mobile services (LMS) and fixed services (FS), and parts of the band has been added to the Radio Regulations frequency allocation table (FAT). Compatibility studies concluded that atmospheric attenuation independent of free-space losses at 275-450 GHz is not sufficient to provide compatibility between FS and RAS operations in the absence of other considerations. The results of the study is also presented in conference papers from the THOR-Project[5] [44][45].

4.6 Spectrum for verticals

5G will be key for digitizing Verticals sectors. [51] As a result of this, the verticals will become an important part of the 5G ecosystem. Telecom operators and the vertical industries mostly have common interests when it comes to 5G. Operators get the opportunity to sell communication services to industries in addition to consumers, and vertical industries get enhanced communication services that improve their efficiency and customer experience. However, one area where the interests of telecom operators and industry player not always coincide is the question of ownership of the spectrum used for 5G.

Spectrum for private LTE and 5G networks is being made available in many countries. In the United States there are efforts ongoing to commercialize the CBRS band.

In the U.K. Ofcom introduced two new license products in July 2019 to make it easier for a wider range of users in the UK to access radio spectrum through local licensing [52]. "Shared Access" licenses give access to spectrum in the 3.8-4.2 GHz, 1800 MHz and 2300 MHz bands and "Local Access" licenses provide access to spectrum that is already licensed to mobile operators but which is not being used or planned for use in a particular area within the next three years. "Shared access" licenses are allocated on a first come, first served basis, and those getting a license must pay a fee that reflects Ofcom's cost of issuing the license. Those getting a "Local access" license will have to pay £950 per licence, which allows them to use the spectrum for three years unless they ask for a different period and this can be agreed with the existing licensees.

In Germany companies has been able to acquire their own frequencies in the 3.7-3.8 GHz band since November 2019 [53][54], where the cost for the spectrum is based on the allocated bandwidth, the duration of the allocation, the size (and type) of the allocation area and a base amount. Bosch is one of the actors who have applied for such a license [55].

Since there are potentially conflicting interests and perspectives between vertical industries and telecom operators regarding spectrum ownership and it is uncertain which part will "win", it is difficult to identify trends when it comes to spectrum for verticals. In fact, any statement on trends will be (perceived as) a spectrum political statement. Hence, in this report the discussion on this topic will be limited to a presentation of the views of the different parties.

[5] https://thorproject.eu/results/conference-papers/

4.6.1 Verticals' view

For some large companies, communication is so vital that they want to invest in their own private networks to have full control over their own infrastructure. They do not want to entrust their entire digitized operations to network operators, but rather take care of the implementation of their own infrastructure and thereby get control of data security and network reliability. Having full control of the 5G infrastructure also ensures that necessary enhancements will be implemented in the network as communication requirements change. Mobile operators serve many types of customers, and some companies are concerned that other customers might have conflicting requirements and be economically more attractive for the operator.

To have full control over the communications many companies see it as necessary to own the spectrum that is used. A telecom operator that uses a certain spectrum in a large area often has to homogenize their services in order to exploit the spectrum efficiently. For example, might the operator want to synchronize its TDD network to avoid large guard bands in the frequency domain, which means that it will be unable or unwilling to offer certain services to only a small local area since this would reduce the wider area performance too much. Hence, some companies see it as necessary to own their own spectrum in order to secure that they can enhance their local network in the future to adapt to changing requirements.

The car industry is an example of a vertical that promote allocation of private spectrum. For this industry, the networked factory is the great hope for productivity increases in the medium term. The sheer quantity of data should give unprecedented control over all aspects of production, allowing factories to switch focus rapidly and with great precision, making different models simultaneously on the same assembly lines. BMW, Volkswagen and Daimler are examples of car manufacturers that have expressed interest in operating private 5G networks for their plants. They argue to the German regulator that if local frequencies are handed out to them for free or a low cost, that would make a real contribution to the competitiveness of their production locations.

4.6.2 Telecom operators' view

Telecom operators, on the other hand, advocate that the most efficient use of the scare spectrum be achieved by having licenses that cover large areas (typically country-wide) and sufficiently large contiguous frequency blocks.

Operators need large contiguous frequency blocks in order to provide the fastest 5G services, 80-100 MHz per operator contiguously in priority mid-bands (e.g. 3.5 GHz) and around 1 GHz in millimeter waves (e.g. 26 or 28 GHz). Setting aside spectrum for industry verticals will limit assignment of large contiguous frequency blocks to operators, which reduce the benefits 5G can offer to the society. GSMA claims that spectrum set aside nationally for vertical industries in pioneer 5G bands such as the 700 MHz, 3.5 GHz or 26 GHz, poses a severe threat to the wider success of 5G.

Operators argue that mixing industrial and commercial networks in the same frequency bands will result in harmful interference or limit the 5G services that can be supported. For example, in spectrum where TDD is used, very high-speed public broadband networks cannot co-exist with very low latency industrial networks in the same area unless large guard bands are used. Operators further argue that they have diverse spectrum assets at their disposal that make them able to provide the communication solutions required in most, if not all, the industry vertical use cases.

The GSMA advocates that instead of setting aside spectrum for industry verticals it would be better to oblige winners of spectrum auctions to provide service that satisfies dedicated local industry vertical needs on a commercial basis or otherwise be mandated to lease the spectrum to them. This solution has already been chosen in Finland and Italy for the 3.4-3.8 GHz and 26 GHz band.

GSMA also points out that using unlicensed or shared spectrum can be a solution for some vertical industries, especially if the communication is taking place indoors where interference can be more easily controlled. In a recent position paper, GSMA points quite clearly out that exclusively licensed spectrum should remain the core 5G spectrum management approach. Spectrum sharing and unlicensed bands can play a complementary role [56].

Conclusions

In this deliverable, we presented an analysis of the emerging wireless technology trends for the evolution of 5G in the short, medium and long terms.

We first presented in chapter 1 the list of key wireless R&D stakeholders considered in this deliverable to capture the different views and trends. Some 25 stakeholders have been identified in the EU, US, and globally. The stakeholders have been classified in three categories: i) Research programmes; ii) Industry and standard forums; and iii) Spectrum regulation organizations.

Next in chapter 2, we presented the forecast on the 5G KPI evolution in the short-term (2022'ish), medium-term (2025'ish) and long-term (2030'ish). These capabilities were benchmarked with the capabilities targeted today by 5G NR, and a gain factor was derived for each capability and for each time scale. For example, the peak data rate was in the first edition of the technology roadmap to multiply with a factor of 5 in the short term, 10 in the medium term and 20 in the long term. Analysing the feedback from the EMPOWER technology roadmap consultation shows how the trends for spectrum, user data rate, connection density, reliability, latency, energy efficiency and positioning accuracy is viewed upon by the scientific community. For example, it is believed that spectrum up to 500 GHz will be available before 2030 by 70%. It is also believed that we will be able to bring down latencies to 0.5 ms, however reaching 0,1 ms is less likely.

In chapter 3, we presented emerging wireless technology trends as surveyed from the wireless research and standardization forums. The key technology trends for the short-term evolution of 5G were derived primarily from the studies around the next batch of future wireless standard releases in 3GPP (e.g. Release 17 and Release 18), and in IEEE (evolution of IEEE 802.11 and IEEE 802.15). The trends showed noticeably a priority set on enhancing the various KPIs such as coverage, throughput, latency, reliability, energy efficiency, and positioning, to extend the support to new emerging use cases such as i) V2X, ii) KPI-demanding industrial IoT, iii) private and dedicate networks, and iv) aerial and satellite networks. Furthermore, it was also noticed a trend to enhance the data collection and exposure from the network and devices to enable data-driven system optimization through artificial intelligence technologies, such as machine learning.

For the longer-term evolution of 5G in the timeframe 2025-2030, the direction of travel was steered more towards disruptive technologies which maturity for standardization and commercial use is difficult to predict soon, making these technologies exciting for fundamental research much desired by the academic and research community. We attempted to capture the trends in five technology areas anticipated to impact 6G, namely i) circuits and devices, ii) radio transceivers, iii) radio access system, iv) network protocols, and v) data and intelligence. The trends in these areas are briefly outlined below:

1) Circuits and devices trending at nanometres level with node scaling targets of Power-Performance-Area-Cost (PPAC) breaking through the limits of Moore's Law.
2) Radio transceivers supporting extreme requirements at Tbps data rates, sub-ms latency, and sub-mWatts power.
3) Radio system expanding to integrate (un)licensed, (non)terrestrial, and (non)communications sub-systems, in a 3-D space with fluid topologies.
4) Network protocols catering for the requirements of next generation internet including determinism, time-sensitivity, and automation.
5) Data (small and big) driving E2E system (network, device and application) optimization with pervasive collaborative intelligence distributed across terminals, edge, fog and cloud.

Following this, we presented a selection of advanced wireless research topics emerging on the roadmap towards 6G and beyond, anticipating that they are representing enablers for the trends in the five areas.

Finally, in chapter 4, we presented an analysis of the trends in radio spectrum, where the trends showed raised importance for operations in unlicensed spectrum both at low and high frequency ranges (e.g. in 60 GHz). The trends also demonstrated a revived interest in spectrum sharing beyond white spaces, towards increasingly geographically localized spectrum deployment (e.g. at high frequencies, or in private networks). The longer-term trends for exploring new spectrum up to THz frequencies were also captured. Updates from ITU WRC-19 shows that massive amounts of spectrum in the mm-wave bands now is being harmonized to meet the demands of 5G and beyond for massive bandwidth, high reliability and low latency, as well as for new communication platforms like LEO-satellite systems and high altitude platforms (HAPS).

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