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ICT - Information and Communication Technologies

Deliverable D2.1

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 first WP2 public deliverable D2.1 of the EMPOWER project comes therefore to capture in brief the emerging wireless technology trends, which will constitute the basis of the first EMPOWER B5G technology roadmap release due in D2.2 in October 2019.

The following summarizes the key topics presented in this deliverable D2.1:

1) Identification of key stakeholders in the R&D communities, in Europe, the USA, 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, despite the figures presented being speculative as there doesn't exist yet an international industry effort (e.g. ITU-R) to set the requirements for future B5G systems.
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 has been earmarked for the commercial roll-out of 5G networks in several countries, noticeably in Europe, the USA, South Korea, Japan and China. 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 more conservative 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 first public deliverable D2.1 of the EMPOWER project comes therefore to present in brief the emerging trends captured, which will constitute the basis of the first technology roadmap release in the next deliverable D2.2.

This deliverable is structured around 4 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.

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 10 research programmes considered in analyzing the trends for B5G.

Table 1-1: B5G research programmes.

No	Stakeholder	Region	Short description
1	H2020 5G-PPP ICT-17, 18, 19, 20	Europe	Programme already in its phase 3 focused on 5G experimental validation and starting research on beyond 5G (paving the way for Horizon Europe). Some 30+ projects are expected across the calls 17/18/19/20.
2	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 is due to conclude in March 2020. A follow-up action is under preparation.
5	6GENESIS	Europe Finland	Finnish research programme on 6G, launched in 2018 and running for 7 years.
6	US NSF	USA	US National Science Foundation supports fundamental research and education in all the non-medical fields of science and engineering including future wireless systems
7	US PAWR	USA	US-IGNITE NSF programme focused on platforms for advanced wireless research, including 4 projects, 2 already launched from phase 1, and 2 expected from phase 2. Programme launched in 2018 until 2024.
8	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.
9	DARPA Spectrum Challenge	USA	DARPA international research challenge on collaborative Intelligent Radio Networks (Using Artificial Intelligence).
10	WWRF	Global	Wireless World Research Forum including over 50 industry and university members mostly from Europe and Asia.
11	5GForum	South Korea	A private-public research organization in South Korea targeting the development and promotion of 5G and beyond mobile technologies.

1.2 Industry and Standards Forums

Table 1-2 gives a list of the top 10 industry and standards forums considered in analyzing the trends for B5G.

Table 1-2: 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.
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 Focus Groups	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.
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.

1.3 Spectrum Regulation Organizations

Table 1-3 gives a list of the top 5 spectrum regulation forums considered in analyzing the trends for B5G.

Table 1-3: 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.
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. B5G Key Performance Indicators

This chapter presents an indicative set of capabilities targeted for 5G evolution in the short-term (2022'ish), medium-term (2025'ish) and long-term (2030'ish). Some capabilities are enhancements to existing capabilities defined in current 5G specifications, whilst others are new capabilities introduced to support anticipated requirements from future use cases noticeably from the vertical industries. The targeted capabilities identified are speculative as there doesn't exist yet an effort to set these as requirements for future B5G systems.

2.1 Targeted KPIs for the short-term evolution of 5G

The short-term evolution (STE) of 5G is commonly attributed to the enhancements envisioned in forthcoming 3GPP 5G specifications releases 17 and 18, thus around the time frame 2022. Table 2-1 presents a summary of the targeted KPI enhancements in 5G STE compared to current 5G [1][2].

As shown in Table 2-1, the STE of 5G is envisioned to double the bandwidth and data rates of current 5G thanks to the expanded spectrum towards the 100 GHz carrier frequency. The spectral efficiency, latency, reliability, density, and mobility are not anticipated to undergo a noticeable enhancement.

Table 2-1: Target KPIs for the short-term evolution of 5G.

Capability	Target in 5G [1][2]	Target in 5G STE	Enhancement factor
Spectrum	<52.6 GHz	<100 GHz	x 2
Bandwidth	<1 GHz	<2 GHz	x 2
Peak Data Rate	(DL/UL) >20/10 Gbps	(DL/UL) >50/25 Gbps	x 2
User Data Rate	(DL/UL) >100/50 Mbps	(DL/UL) >100/50 Mbps	x 2
Spectral Efficiency	(DL/UL) >30/15 bps/Hz	(DL/UL) >30/15 bps/Hz	x 1
Traffic Capacity	20 Mbps/sqm	40 Mbps/sqm	x 2
Density	>1 device/sqm	>1 device/sqm	x 1
Reliability	>99.999%	>99.999%	x 1
U-Plane Latency	<1 ms	<1 ms	x 1
C-Plane Latency	<10 ms	<10 ms	x 1
Power (Terminal)	<100's mWatts	<100's mWatts	x 1
Positioning accuracy	<30 cm	<30 cm	x 1
Mobility	<500 Km/h	<500 Km/h	x 1

2.2 Targeted KPIs for the medium-term evolution of 5G

The medium-term evolution (MTE) of 5G is anticipated to bring significant enhancements to today's 5G whilst remaining fully backwards compatible, thus targeting future 3GPP releases 19 and 20 around the time frame 2025. Table 2-2 presents a summary of the targeted KPI enhancements in 5G MTE compared to current 5G [1][2].

As shown in Table 2-2, the MTE of 5G is envisioned to multiply by 10 the current 5G throughput, thanks to larger bandwidths that may be exploited in with spectrum below 500 GHz. In addition to traditional KPIs of throughput, latency and reliability, 5G MTE is anticipated to achieve significant reduction (a factor of 10) to terminal power consumption and a significant enhancement to positioning accuracy below the 10 cm threshold. It is also noteworthy in 5G MTE the redefinition of some KPIs such as traffic capacity and density from a 2D area/square meter measure to a rather 3D volume/cubic meter measure, reflecting on the expansion of 5G to cover spatial (flying) terminals, base stations, and network infrastructures.

Table 2-2: Target KPIs for the medium-term evolution of 5G.

Capability	Target in 5G [1][2]	Target in 5G MTE	Enhancement factor
Spectrum	<52.6 GHz	<500 GHz	x 10
Bandwidth	<1 GHz	< 5 GHz	x 5
Peak Data Rate	(DL/UL) >20/10 Gbps	(DL/UL) >200/100 Gbps	x 10
User Data Rate	(DL/UL) >100/50 Mbps	(DL/UL) >500/250 Mbps	x 5
Spectral Efficiency	(DL/UL) >30/15 bps/Hz	(DL/UL) >60/30 bps/Hz	x 2
Traffic Capacity	20 Mbps/sqm	100 Mbps/cum	x 5
Density	>1 device/sqm	>5 device/cum	x 5
Reliability	>99.999%	>99.9999%	x 10
U-Plane Latency	<1 ms	<0.5 ms	÷ 2
C-Plane Latency	<10 ms	<5 ms	÷ 2
Power (Terminal)	<100's mWatts	<10's mWatts	÷ 10
Positioning accuracy	<30 cm	<10 cm	÷ 3
Mobility	<500 Km/h	<1000 Km/h	x 2

2.3 Targeted KPIs for the long-term evolution of 5G

The long-term evolution (LTE) of 5G is analogous to what the research community has dubbed as 6G, hence more disruptive with significant enhancements around the time frame 2030. Table 2-3 presents a summary of the targeted KPI enhancements in 5G LTE compared to current 5G [1][2].

As shown in Table 2-3, the LTE of 5G is envisioned to target radical improvements compared to today's 5G, which require a breakthrough in disruptive technologies that are not mature yet in the sort and medium terms horizon. In terms of KPIs, 5G LTE is therefore envisioned to ambitiously aim for Tbps throughput through ultra large bandwidths (in the order of 10 GHz) that may be available in the spectrum up to 1 THz (1000 GHz). 5G LTE is also set to achieve micro-seconds latency in the user plane, thus supporting a wide range of tactile applications not possible today with 5G. Ambitious KPI targets are also set for terminal power consumption (sub-mWatt) and positioning accuracy (sub-ms), in addition to ambitious targets for 3D-volumetric traffic capacity and density.

Table 2-3: Target KPIs for the long-term evolution of 5G.

Capability	Target in 5G [1][2]	Target in 5G LTE	Enhancement factor
Spectrum	<52.6 GHz	<1000 GHz	x 20
Bandwidth	<1 GHz	< 10 GHz	x 10
Peak Data Rate	(DL/UL) >20/10 Gbps	(DL/UL) >1000/500 Gbps	x 50
User Data Rate	(DL/UL) >100/50 Mbps	(DL/UL) >2000/1000 Mbps	x 20
Spectral Efficiency	(DL/UL) >30/15 bps/Hz	(DL/UL) >100/50 bps/Hz	x 3
Traffic Capacity	20 Mbps/sqm	1000 Mbps/cum	x 50
Density	>1 device/sqm	>10 device/cum	x 10
Reliability	>99.999%	>99.99999%	x 10
U-Plane Latency	<1 ms	<0.1 ms	÷ 10
C-Plane Latency	<10 ms	<1 ms	÷ 10
Power (Terminal)	<100's mWatts	<1 mWatt	÷ 100
Positioning accuracy	<30 cm	<1 cm	÷ 30
Mobility	<500 Km/h	<1000 Km/h	x 2

3. Wireless Technology Trends

This chapter presents emerging wireless technology trends as surveyed from the wireless research and standardization forums and attempts an initial classification of these enabling technologies in accordance with the three timescales set out for the evolution of 5G, namely short-term, medium-term, and long-term.

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 [3][4][5]. 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 Q1'2020. 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

The 3GPP has recently (June 2019) held its workshop with the aim to define the specification agenda for the next Release 17. Several topics have been presented as summarized in the Table 3-1 below.

Table 3-1: 5G NR enhancements targeted in Release 17 (2020-2021).

No	Targeted NR enhancement	Short description
1	NR-Lite	Targeting enhancements noticeably in power saving for optimal operation in mid-tier NR devices (e.g. wearables, surveillance cameras)
2	Above 52.6 GHz	Targeting new waveform decision for spectrum above 52.6 GHz including 60GHz unlicensed
3	Side-link	Targeting maximum commonality between commercial, V2X, and Critical Communication usage of side-link while addressing their specific requirements
4	Extreme coverage	Targeting extreme coverage requirements both indoor and outdoor
5	Multicast / Broadcast	Targeting multi-cast/broadcast enhancements for V2X and Public Safety
6	URLLC	Targeting enhancements for industrial IoT (wider use cases)?
7	MIMO	Expand use cases E.g. Support for cases with high speed mobility, better support for FDD
8	NTN	Scoping of the normative WID. Include NTN-specific positioning

9	Integrated Access Backhaul	Includes duplexing enhancement; Potentials for network coding; Mobile IAB
10	Unlicensed spectrum	Generic unlicensed operation enhancements not covered by any other item are addressed here;
11	Power saving	Enhancements for power saving of smartphones; Network power saving aspects as a separate sub-discussion;
12	Positioning	Factory/campus positioning, IoT, V2X positioning, 3D positioning, cm level accuracy, incl latency and reliability improvements; NR-U positioning aspects; Idle and inactive
13	Data collection	Includes SON and MDT; Data collection to enable AI is part of this discussion

Whilst it is too early to define the scope of Release 18, a potential list of topics is attempted 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 [5]:

- 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

Whilst 802.11ax and 802.11ay are nearing completion (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. 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 (WiFi 6)

The IEEE 802.11ax, also known as WiFi 6 (the sixth generation WiFi), 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 4x 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.

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.

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

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 centimeters 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 has already been 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.

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 [6]-[15]. These technologies target the KPIs outlined previously in section 2.2 and section 2.3, 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 intelligent 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 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 nanometers 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)comms 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.

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 as clearly evidenced in the THz cluster in H2020, the DARPA T-MUSIC programme, IEEE 802.15 THz interest group, and the FCC in the US recently announcing giving experimental licenses for spectrum above 95 GHz.

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" surfaces into the environment (such as 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 1000 miles above the Earth's surface. Today, there are a few thousands 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 their capabilities will be significantly enhanced by advances in manufacturing, robotics, energy, and artificial intelligence. 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.

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.

3.2.4 Wireless power transfer and Energy harvesting

Wireless power transfer 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.

3.2.5 Federated Artificial Intelligence

Artificial Intelligence 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. This trend will accelerate and move from a big data-driven centralized approach today to a more small data-driven distributed approach in 6G, where concepts such as federated AI are envisioned to: i) alleviate the issues of collecting big data to train the models in centralized data centers, 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.

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. The next decade is promising significant advancements to quantum devices so they can operate at normal temperatures.

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 Cisco Visual Networking Index (VNI) global mobile traffic forecast [17] and the Ericsson Mobility Report [15] forecasts 77 EB (ExaBytes) global monthly traffic in 2022 and 131 EB in 2024.

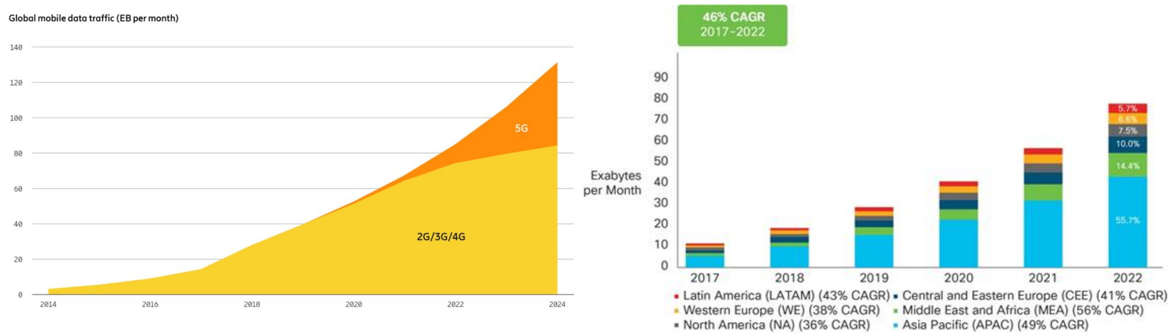

Figure 4-1 Ericsson Mobility Report [15] (left) and Cisco VNI [17] mobile data traffic forecasts.

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. 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 been increased, the percentage of Wi-Fi offload is expected to increase when moving to 5G:

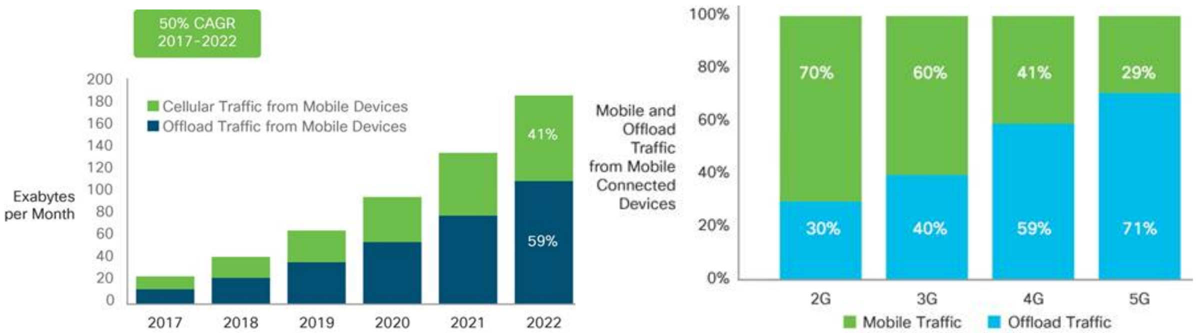

Figure 4-2 Cisco VNI forecast of so-called offload traffic from cellular to other wireless networks, typically Wi-Fi [17].

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.

Recently, ITU launched the "ICT Regulatory Tracker"[1] [18], which 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

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

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:

- **EU Radio Spectrum Policy Group (RSPG):** The Radio Spectrum Policy Group (RSPG) is a high-level advisory group that assists the European Commission in the development of radio spectrum policy.
- **Networld2020 ETP Vision Group:** 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.
- **The Federal Communications Commission (FCC):** FCC is an independent U.S. government agency overseen by Congress. It is the federal agency responsible for implementing and enforcing America's communications law and regulations. It regulates interstate and international communications by radio, television, wire, satellite, and cable in all 50 states, the District of Columbia and U.S. territories.
- **Ofcom:** 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.
- **The International Telecommunications Union Radio Sector (ITU-R):** ITU-R'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.
- **GSM Association (GSMA):** 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-PPP Spectrum Working Group:** 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 other Global project results concerning advances in spectrum research. Liaise with spectrum groups or entities in regulatory bodies and industry associations.

4.2 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. One of the agenda items for ITU-R World Radiocommunication Conference 2019 (WRC-19)[2] is addressing the band from 5.150 to 5.925 GHz. This band 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. WRC19 agenda item 1.16 will discuss the regulations for the whole band based on sharing and compatibility studies. The studies have proposed some changes or options for changes to the Radio Regulations (RR), including the option of "No Change" (NOC) [19].

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. 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.

[2] https://www.itu.int/en/ITU-R/conferences/wrc/2019/Pages/default.aspx

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

4.3 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[3] is discussing spectrum sharing and reutilization in their Vision Paper [6]. 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.

The 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/Licensed Shared Access
- Pluralistic licensing
- Citizens Broadband Radio Service (CBRS)

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

In ECC Report 80 [23] 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

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

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, described light licensing in the following way in [24]:

"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 so not interfere with existing transmitters or oblige the user to coordinate their deployment with other registered users

In any case, light licensing permits typically greater power than licence-exempt regimes.

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 [22] 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)*".

Pluralistic licensing
In [26] 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 [26]. 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).

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.

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.

4.4 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 and above and we divide into so-called millimeter-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 was identified for IMT at WRC-15. Sharing studies has been performed and will be discussed under Agenda Item 1.13 at WRC-19

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.

Regarding the THz frequencies, the band from 275 to 450 GHz will be discussed as WRC-19 agenda item 1.15 for land mobile services (LMS) and fixed services (FS). This band is partly used by the Earth Exploration Satellite Service (EESS) and radio astronomy services (RAS) for passive use.

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[4] [20][21].

4.5 Spectrum for verticals

5G is expected to play an important role enabling modernization of several industries. 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 is evaluating a spectrum sharing framework spanning multiple bands [27] and the German regulator is evaluating the 3.7-3.8 GHz band for "localized" private 5G networks for industrial use [28].

Since there is a strong conflict of interest 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 two parties.

4.5.1 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.

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

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.

4.5.2 Telecom operators' view

Telecom operators, on the other hand, advocate that the most efficient use of the scare spectrum is 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.

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 an indicative set of capabilities to be targeted for 5G 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 targeted peak data rate was envisioned to double in the short-term evolution of 5G, multiply by 10 in the medium-term, and by 50 in the longer term reaching the Tbps mark. The target figures presented are speculative and were derived from the ambition to: i) achieve much higher performance in every current KPI dimension compared to 5G NR, and ii) add new capabilities by redefining some current KPI dimensions or adding new KPI dimensions to the design space.

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 nanometers 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)comms 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.

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.

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