Towards 6G: Evolution of Key Performance Indicators and Technology Trends

Alain Mourad
InterDigital Europe Ltd
alain.mourad@interdigital.com

Rui Yang
InterDigital Inc.
rui.yang@interdigital.com

Per Hjalmar Lehne
Telenor Research
per-hjalmar.lehne@telenor.com

Antonio de la Oliva
University Carlos III of Madrid
aoliva@it.uc3m.es

***Abstract*— This paper presents a study on the evolution of Key Performance Indicators (KPIs) and technology trends towards 6G. Three timescales are considered, namely short-term (2022'ish), medium-term (2025'ish), and long-term (2030'ish). The evolution of these KPIs is analyzed by accounting for forecasts on the emerging use cases and their requirements together with assumptions on the pace of wireless technology advancements. Being intrinsically predictive, we cannot assert with certainty the values of the target KPIs and the shortlisting of the Top-10 wireless technology trends. It is, however, aimed at driving discussions and collecting feedback over the next decade. Future refinement is therefore expected as the 5G NR evolution journey progresses towards 6G.**

Keywords—5G, 6G, KPI, Wireless, Evolution.

I. 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) community has started to lay out the agenda for what is coming up next beyond 5G (B5G). This agenda varies in time scales in accordance with the inherently different time horizons typically targeted by the different wireless R&D stakeholders. For example, whilst the more visionary research community is setting focus on the longer-term 6G research with a ten-years' time-horizon towards 2030, the industry R&D stakeholders are rather focusing on the short to medium term enhancements of current 5G system specifications with up to 5 years' time-horizon.

The H2020 EMPOWER project [1] is an initiative launched recently (November 2018) in Europe with the aim to capture the trends and advancements in wireless research including experimental tools for B5G systems. This paper presents first results from a study carried out in EMPOWER on the evolution of 5G NR Key Performance Indicators (KPIs) for the shorter, medium and longer -term evolution of 5G NR. The KPIs evolution is analyzed by accounting for forecasts on the emerging use cases and their requirements together with assumptions on the pace of wireless technology advances.

The rest of this paper is organized as follows. Section II first captures some key emerging use cases and forecasts on requirements from the end-user space and industry vertical space. Section III next presents in details our forecasts of the target KPIs evolution of 5G NR. Section IV follows with key technology trends envisioned to meet the target KPIs. Our conclusions and next steps are presented in Section V.

II. Emerging Use Cases and Requirements

With the aim to motivate the evolution of B5G target KPIs, we start first by capturing some trends in emerging use cases and their requirements. Several use cases are emerging both in the end-user applications space and in the vertical applications space, such as: i) Autonomous vehicles and swarm systems, ii) Connected industries and automation, iii) Aerial and satellite networks and platforms, iv) Volumetric media streaming, and v) Multi-sensory extended reality and haptics. These use cases and any future use cases are expected to continue to require the same kind of 5G KPIs, but with: a) new target values (e.g. higher data rate, lower latency, better reliability, etc.); and b) new hybrid profiles cutting across the three basic 5G service types, namely, eMBB (enhanced mobile broadband), URLLC (ultra-reliable and low latency communication), and mMTC (massive machine type communication).

A. Forecasts in the End-User Space

In the end-user space, the forecast for the user average monthly data consumption in 2024 is approximately 20 GB compared to approximately 6 GB today [2]. The most data consuming applications will continue to be video streaming based, with a total of 15 GB in user average monthly data consumption in 2024 compared to 3.5 GB today. The top video streaming user applications contributing to this dramatic increase in 2024 include: i) 1080p Full HD (1920x1080); ii) 360° Video – 720p HD; iii) Virtual Reality (VR) Full HD; and 4K UHD (3840x2160). Beyond 2024, it is envisioned that there will be even more demanding video streaming applications which will take the user traffic to new levels such as: i) 8K UHD (7680x4320); and ii) Volumetric media streaming. This forecast gives therefore an increase in user traffic of approximately 5 times in 5 years until 2024, which, if extrapolated linearly to 2030, would lead to an increase factor between 20 and 30 times the user traffic today. This growth factor is used in the next section to support our forecast of the new target KPI values noticeably for spectrum, bandwidth, data rates, and area traffic capacity.

B. Forecasts in the Industry Verticals Space

The rich diversity of the targeted industry verticals is one of the main differentiators between 5G and B5G compared to previous generations. Various forums such as 5GAA (5G Automotive Association) [3] and 5GACIA (5G Alliance for Connected Industries and Automation) [4] have already been active in defining their use cases and requirements, and channeling these into 5G standardization development organizations, primarily 3GPP (Third Generation Partnership Project) [5]. This is clearly evidenced in 3GPP 5G specifications through the enhancements of cellular V2X (Vehicle to Everything) and the introduction of NR-light to

978-1-7281-6047-4/20/$31.00 ©2020 IEEE

capture new device types encountered primarily in vertical applications such as smart factories.

The verticals space is characterized by a very large number of different use cases with, sometimes, very diverse requirements for wireless communications. Taking manufacturing as an example in vertical domain, which is forecasted to be one of the largest and fastest growing market for 5G and its evolution in the next 5 years [6][7], there are several use cases which are spread across the 5G services triangle side joining eMBB and URLLC vertices [7]. To appreciate the diverse requirements in the manufacturing use cases, TABLE I provides a sample of the KPI requirements extracted from [6][7].

TABLE I. SAMPLE OF KPI REQUIREMENTS FROM THE MANUFACTURING VERTICAL USE CASES.

KPI	Requirement
Data rate	Up to several Gbps
End-to-End latency	Varies from 0.5 to 500 ms
Time synchronicity	Down to 1 us
Reliability	Varies from 3 up to 8 nines

As reported in TABLE I, the requirements of the different manufacturing use cases vary drastically for each KPI with stringent values including for example i) down to 0.5 ms latency, ii) up to 8 nines reliability, and iii) down to 20 cm positioning accuracy. These requirements are used in the next section to support our forecast of the new target KPI values noticeably for reliability, latency, and positioning.

III. B5G TARGET KPIS EVOLUTION

TABLE II summarizes our forecast of the B5G target KPIs evolution for the short (SEVO), medium (MEVO), and long (LEVO) -term evolution of 5G, compared to the KPIs targeted in today's 5G New Radio (NR).

TABLE II. TARGETED KPIS FOR THE SHORT, MEDIUM, AND LONG -TERM EVOLUTION OF 5G NR.

Target KPI	5G NR	5G NR SEVO	5G NR MEVO	5G NR LEVO
Spectrum	<52.6 GHz	<250 GHz	<500 GHz	<1000 GHz
Bandwidth	<0.5 GHz	<2.5 GHz	<5 GHz	<10 GHz
Peak Data Rate	DL: >20 Gbps UL: >10 Gbps	DL: >100 Gbps UL: >50 Gbps	DL: >200 Gbps UL: >100 Gbps	DL: >400 Gbps UL: >200 Gbps
User Data Rate	DL: >100 Mbps UL: >50 Mbps	DL: >500 Mbps UL: >250 Mbps	DL: >1 Gbps UL: >0.5 Gbps	DL:>2 Gbps UL: >1 Gbps
Peak Spectral Efficiency	DL: >30 bps/Hz UL: >15 bps/Hz	DL: >40 bps/Hz UL: >20 bps/Hz	DL: >50 bps/Hz UL: >25 bps/Hz	DL: >60 bps/Hz UL: >30 bps/Hz
Density	>1 device/sqm	>1.3 device/sqm	>1.7 device/sqm	>2 device/sqm
Area Traffic Capacity	> 10 Mbps/sqm	>50 Mbps/sqm	>100 Mbps/sqm	>200 Mbps/sqm
Reliability	URLLC: >5 nines	>6 nines	>8 nines	>9 nines
U-Plane Latency	URLLC: <1 ms	<0.5 ms	<0.2 ms	<0.1 ms
C-Plane Latency	<20 ms	<10 ms	<4 ms	<2 ms
Net. Energy Efficiency	Qualitative	>30 % gain	>70 % gain	>100% gain
Term. Energy Efficiency	Qualitative	>30 % gain	>70 % gain	>100% gain
Mobility	<500 Km/h	<500 Km/h	<500 Km/h	<1000 Km/h
Positioning accuracy	NA (<1 m)	<30 cm	<10 cm	<1 cm

Below, we present the logic adopted in our forecast of the target values for each of the KPIs in Table 2. It is noteworthy that all the KPIs are not new, but their target values are envisioned to evolve in the various phases of 5G NR evolution.

A. Spectrum and Bandwidth

1) Spectrum frequency

The current 3GPP 5G NR releases (Rel-15 and Rel-16) operate in a spectrum below 52.6 GHz. This cap is already lifted in the upcoming Rel-17, but there hasn't been yet an agreement on the new cap, whether it will be 100 GHz or 250 GHz. We therefore set the target threshold of the spectrum cap in SEVO reasonably to 250 GHz, especially as there is already standardization work in this space both in IEEE and ETSI. As we referred in D2.1 [1], a study on the spectrum band 275-450 GHz will be discussed at this year's WRC-19 in October 2019. This is anticipated to underpin the MEVO target. For the 5G LEVO, we extrapolate the MEVO target next to 1000 GHz (1 THz) in line with the active research interest in sub-THz communications detected in the wireless research community.

2) Bandwidth

The bandwidth was derived in accordance with the Spectrum KPI and it represents a single channel bandwidth thus does not include any aggregation. Today in 3GPP 5G NR, the channel bandwidth may go up to 0.5 GHz (to be precise 400 MHz = 0.4 GHz) in the FR2 spectrum below 52.6 GHz. We therefore anticipate the bandwidth to multiply by 5 to up to 2.5 GHz in the 5G SEVO in line with bandwidth availability in the 50-250 GHz spectrum range. This 2.5 GHz target channel bandwidth comes also in line with what exists in standards today such as in IEEE 802.11ay, where the single channel bandwidth is 2.16 GHz in the 60 GHz spectrum. Further on, the single channel bandwidth is envisioned to go up to 5 GHz in the 250-500 GHz spectrum, and further up to a staggering 10 GHz in the 500-1000 GHz (THz) spectrum. It is noteworthy that in our target bandwidth setting in SEVO, MEVO, and LEVO, we have kept the ratio of frequency/bandwidth constant to approximately a factor of 100 (approximately equal to 52.6/0.5, 250/2.5, 500/5, 1000/10). This prediction aligns with the growth in average user data consumption outlined in section 2.1 where it is forecast a growth factor of approximately 5-10 times, 10-20 times, and 20-30 times in 2023-2024, 2025-2027, and 2027-2030, respectively.

B. Peak Data Rate, User Data Rate and Peak Spectral Efficiency

1) Peak Data Rate

The peak data rate is obtained simply by scaling linearly with the bandwidth KPI. In 5G SEVO, by multiplying by 5 the bandwidth from 0.5 GHz to 2.5 GHz, we anticipate the peak data rate to also multiply by 5 to 100 Gbps and 50 Gbps, respectively for downlink and uplink, up from 20 Gbps and 10 Gbps in 5G NR today. These targets come in line with what is achievable today for example in IEEE 802.11ay where a peak data rate of about 70 Gbps in downlink is achievable in 2.16 GHz channel. In 5G MEVO, as the bandwidth multiplies by up to a factor of 2 compared to SEVO, the peak data rate is anticipated to scale accordingly reaching 200 Gbps and 100 Gbps, in downlink and uplink respectively. Further on, for 5G LEVO, the bandwidth is further multiplied by 2 compared to MEVO, and so the target peak data rate is scaled accordingly to 400 Gbps and 100 Gbps in downlink and uplink respectively.

2) User Data Rate

Like the peak data rate above, without channel aggregation, the user data rate is assumed to scale linearly with the bandwidth. It is therefore envisioned to go up from (DL: 100 Mbps; UL: 50 Mbps) today in 5G to (DL: 500 Mbps; UL: 250 Mbps) in 5G SEVO, and next to (DL: 1 Gbps; UL: 0.5 Gbps) in 5G MEVO, and further next to (DL: 2 Gbps; UL: 1 Gbps) in 5G LEVO. This prediction aligns with the requirements outlined in section II - A for the end-user video streaming applications and some of the exemplary manufacturing use cases in section II - B.

3) Peak Spectral Efficiency

The evolution of the peak spectral efficiency from today's 5G targets is derived based on the assumption of an approximately 30% improvement in average every 3 years, in line with the historical evolution from 2G to 3G to 4G to 5G. Starting from today's 5G targets of (DL: 30 bps/Hz; UL: 15 bps/Hz), the targets are envisioned to go up to (DL: 40 bps/Hz; UL: 20 bps/Hz), (DL: 50 bps/Hz; UL: 25 bps/Hz), (DL: 60 bps/Hz; UL: 30 bps/Hz), in 5G SEVO, MEVO, and LEVO, respectively.

C. Density and Area Traffic Capacity

1) Density

The evolution of the density from today's 5G target of 1 device per sqm is primarily driven by the proliferation of connected sensors and objects including flying objects such as drones. It is not straightforward to project the density in the volumetric space (per cubic meter) so we opted to stick to the density as defined today per sqm, and any flying object would be accounted for through its 2-D footprint projection. This is also justified by the forecast that the Unmanned Aerial Vehicles (UAV) market is expected to be significantly smaller in terms of number of devices (e.g. <10Million units annual by 2026 according to ABI research). Based on recent forecasts [4], around 34 billion connected devices are forecast by 2024, of which about 22 billion will be related to the IoT. Connected IoT devices include connected cars, machines, sensors, consumer electronics and wearables. The forecast in [4] assumes a growth of approximately 10% year-on-year. We therefore applied an increase factor of 30%, 70% and 120% in 5G SEVO, MEVO, and LEVO, respectively, leading to target densities of 1.3 devices per sqm, 1.7 devices per sqm, and 2 devices per sqm, respectively.

2) Area Traffic Capacity

The evolution of the area traffic capacity is assumed to scale linearly with the peak data rate but also with the network densification. As we move high in frequencies, the distance range is anticipated to shrink, and further network densification would be expected. The deployment environment (e.g. indoor, outdoor) and the types of devices and their density are also anticipated to influence the area traffic capacity targets. For the sake of simplicity, we assumed a network densification growth factor of approximately 30% every three years, in line with the above assumptions for growth in peak spectral efficiency and devices density. We then took this network densification growth factor in conjunction with the bandwidth growth factor and started from today's 5G target of 10 Mbps per sqm. This led to the following targets of approximately 70 Mbps per sqm, 170 Mbps per sqm, and 450 Mbps per sqm, respectively for in 5G short, medium, and long -term evolutions.

D. Reliability and Latency

1) Reliability

The target for reliability today in 5G NR is 5 nines for the URLLC profile. This target is anticipated to evolve gradually to new highs especially as new time-sensitive verticals are considered. Ultimately the vision here is for wireless to replace fiber or cable in these time-sensitive and mobile use cases, in the same way the vision has been for wireless to deliver fiber-like Gbps data rates. We therefore envision the reliability target to reach 9 nines in the long term. The evolution of the reliability target is therefore derived by assuming a gain of 1 nine every 3 years, leading to 6 nines for 5G SEVO, 8 nines for 5G MEVO, and 9 nines for 5G LEVO. This prediction aligns with the requirements outlined in section 2.2 for exemplary manufacturing use cases.

2) U-plane latency

Today in 5G NR, the URLLC target for U-plane latency is 1ms. Like reliability, we envision more and more time-sensitive vertical use cases to drive the evolution of the latency KPI. Without knowing the requirements of the use cases, it is hard to come up with precise target figures for the latency. We therefore use the following reasoning in our derivation; as the bandwidth increases, there is potential for the symbol duration to decrease accordingly. Thus, especially through concepts like the mini-slot in 5G NR, one might consider relating the achievable latency with the symbol duration. We therefore start our derivation of the future user-plane latency targets in 5G SEVO by assuming the most stringent requirement of 0.5 ms outlined in section 2.2 for manufacturing use cases. For 5G NR MEVO, we assumed a further reduction down to 0.2 ms in line with the forecasted increase in channel bandwidth (thus decrease in symbol duration). For 5G NR LEVO, we also assumed a further reduction down to 0.1 ms in line with the forecasted increase in channel bandwidth. These targets also align with the latency targets in time-sensitive fronthaul (few 100 usec) which are achievable today using millimeter-wave fronthaul over a few hundred meters.

3) C-plane latency

Control plane (C-plane) latency is typically measured as the transition time from different connection modes, e.g., from idle to active state, in such a way that the U-plane is established. The target C-plane latency in IMT-Advanced was less than 100 ms when the U-plane latency target was less than 10 ms. In IMT-2020, the target C-plane latency was less than 20 ms and encouraged to go below 10 ms when the U-plane latency target was below 1 ms (URLLC). There are several factors that impact the C-plane latency, such as the distance between the UE and the gNB, and processing delays at both the UE and gNB. Since the distance between the UE and the gNB is anticipated to shrink as the 5G spectrum evolves towards 100s of GHz, and that the processing power of devices and nodes is anticipated to expand, one could easily see the potential for the C-plane latency to reduce further and further. Starting from 20 ms (ideally 10 ms) C-plane latency target in 5G today, the targets for 5G SEVO, MEVO, and LEVO are envisioned to go below 10 ms, 4 ms, and 2 ms, respectively. This represents a reduction in 5G LEVO of 5-10 times compared to 5G today, which is in line with the reduction of 5-10 times in IMT-2020 (10-20 ms) compared to IMT-Advanced (100 ms).

E. Energy Efficiency

1) Network energy efficiency

There is no quantitative target for network energy efficiency in 5G today. The target is more qualitative and aims at minimizing the radio access network energy consumption in relation to the traffic capacity provided. Like the spectral efficiency, we derived the target network energy efficiency based on the assumption of an approximately 30% improvement in average every 3 years. This improvement is enabled by various mechanisms such as higher sleep ratios, switch on-off gNBs, energy harvesting, etc..

2) Terminal energy efficiency

Like the network energy efficiency there is no quantitative target for the terminal energy efficiency in 5G today. The target is qualitative and aims at minimizing the power consumed by the device modem in relation to the traffic characteristics. We have therefore adopted the same assumption of an improvement of 30% every 3 years for the terminal energy efficiency, where such improvement is enabled by various mechanisms such as higher sleep ratios, zero-energy companion transceivers, energy harvesting, etc.

F. Mobility

The targeted mobility in 5G today is up to 500 Km/h. This already covers most of the connected objects including flying objects such as drones. We therefore anticipate this target to remain unchanged at least for the 5G SEVO and 5G MEVO. For the longer term however, there is the assumption that in the future we will have flying objects travelling in excess of 500Km/hr (e.g. UAVs, airplanes) which might need to be supported, hence the target of 1000 Km/h is envisioned for 5G LEVO.

G. Positioning Accuracy

There is no target today in 5G for positioning accuracy, despite 3GPP trying to achieve <3 m level accuracy to improve 5G NR location awareness. Several vertical use cases however especially in industrial control require below 1 m-level (down to below 200 cm) positioning accuracies as outlined for the manufacturing use cases in section 2.2. This comes in line with the targets set in IEEE 802.11az (next generation positioning) to go down to less than 100 cm in the next few years. In current discussions on enhanced positioning 3GPP Rel-17, there is mention of 10 cm to 30 cm accuracy for several use cases. The move to higher frequencies and wider bandwidths is anticipated to increase the positioning accuracy. Furthermore, cm-level accuracy is achievable today through sensing mechanisms (e.g. LiDAR). It is therefore our view that 5G evolution will ultimately try to achieve this cm-level accuracy, mainly thanks to higher spectrum with integrated sensing and communication. The target accuracy is therefore envisioned to improve to below 30 cm, 10 cm, and 1 cm, in 5G SEVO, MEVO, and LEVO, respectively.

IV. Technology Trends

TABLE III provides a shortlist of Top-10 wireless technology trends, for the short, medium and long -term evolution of 5G (SEVO, MEVO, LEVO). The shortlisting of the Top-10 technologies is based on a qualitative assessment of the added value envisioned for a given technology trend in each B5G phase compared to previous phases.

TABLE III. Top-10 wireless technology trends for 5G SEVO, MEVO and LEVO.

No	5G SEVO Trends – Top 10	5G MEVO Trends – Top 10	5G LEVO Trends – Top 10
1	Transmission schemes at mmWave frequencies above 52.6GHz up to 250GHz	Transmission schemes at mmWave frequencies above 250GHz up to 500GHz	Transmission schemes at mmWave frequencies above 500GHz up to 1THz
2	Massive MIMO with antenna arrays of up to 512 elements	Massive MIMO with antenna arrays of up to 1024 elements including distributed arrays	Massive MIMO with antenna arrays of thousands of elements
3	Enhancements to support lower latency (<0.5 ms) and us-level synchronization	Highly energy efficient waveforms and modulations in low and high frequency ranges	Cognitive selection of advanced modulation, coding, and waveforms
4	Unlicensed spectrum and dual-connectivity across licensed-unlicensed spectrum	Multi-connectivity composing from multiple RATs in licensed and unlicensed spectrum	Cognitive integrated access across cellular and non-cellular evolutions of NR, WiFi, and LiFi
5	Integrated Access and Backhaul (IAB) enhancements	In-band full duplexing for gNB and some UE categories	Cognitive dynamic duplexing and carrier aggregation
6	Extended support of NR-light (mid-range) devices	Support of UAVs/drones as UEs, gNBs, and relays	Support of swarms of different devices and device types
7	Device and network power savings enhancements	Ultra-low energy devices and networks supporting energy harvesting capabilities	Battery-less devices and networks providing support of wireless power transfer
8	Support of Non-Terrestrial Networks (NTNs)	Integration of Terrestrial and Non-Terrestrial Networks	Support of Massive VLEO

			satellites and HAPs
9	Data Collection from the core, RAN and UE to enable fusion with AI/ML	Wireless Fusion with AI/ML limited to C-plane and higher layers of stack in the U-plane	Wireless Fusion with AI/ML in every plane and every layer of stack including PHY
10	Communication-based positioning accuracy <30 cm	Joint sensing and communication	Integration of communication, sensing, imaging and radar

The key technology trends for the short (SEVO) and medium (MEVO) -terms evolution of 5G are derived primarily from the studies around future wireless standards noticeably 3GPP (Rel-17, Rel-18 and beyond), and IEEE 802 (evolution of .11 and .15). In both 3GPP and IEEE 802, 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 towards more emerging use cases such as i) V2X, ii) KPI-demanding industrial IoT, iii) private networks, and iv) aerial and satellite networks [9][10][11]. 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.

For the longer-term evolution (LEVO) of 5G, the trends are steered towards disruptive technologies which maturity is difficult to predict at present. At the macroscopic level, these trends include a) the design of disruptive radio transceivers supporting extreme requirements such as Tbps data rates, sub-ms latency, and sub-mWatts power; and b) the integration of various wireless sub-systems together, such as licensed and unlicensed, terrestrial and non-terrestrial, communication and non-communication (sensing, radar, imaging). All this is envisioned with pervasive artificial intelligence everywhere in the wireless system design and operation.

V. CONCLUSIONS AND NEXT STEPS

This paper presented a study on the evolution of 5G NR KPIs and technology trends in the in the short-term (2022'ish), medium-term (2025'ish) and long-term (2030'ish) towards 6G. The evolution of the target KPIs was based on forecasts for the requirements from emerging use cases and on the pace of wireless technology advances. All the KPIs studied are not new (e.g. spectrum, bandwidth, spectral efficiency, data rates, density, traffic capacity, latency, reliability, energy efficiency, positioning accuracy, etc.), but their target values are envisioned to evolve in the various phases of 5G NR evolution. Such evolution is speculative and derived from the ambition to continuously achieve higher performance for each KPI. This is with the aim to provide 6G with the flexibility to support a wide diversity of future use cases both in the end-user space and vertical industry space, where various very high performances might be required for certain KPIs.

The Top-10 wireless technology trends were then captured in each phase of 5G NR evolution. The details of which KPIs are targeted by which technology trend identified, and what are the anticipated gains, trade-offs, and maturity timelines, is an ongoing work by the authors. This work is targeted at the creation of a baseline B5G wireless technology roadmap consolidating the views from the wireless research, standardization and radio spectrum forums.

ACKNOWLEDGMENT

This work has been partially funded by the H2020 EMPOWER project (Grant #824994).

REFERENCES

[1] EMPOWER https://www.advancedwireless.eu/

[2] Ericsson Mobility Visualizer, https://www.ericsson.com/en/mobility-report/mobility-visualizer

[3] 5G Automotive Association (5GAA), www.5gaa.org

[4] 5G Alliance for Connected Industries and Automation (5GACIA), www.5g-acia.org

[5] Third Generation Partnership Project (3GPP), www.3gpp.org

[6] 5GACIA, "5G for Connected Industries and Automation", Second Edition, February 2019.

[7] 5GACIA, "5G for Automation in Industry", July 2019.

[8] Qualcomm, "Expanding the 5G NR ecosystem – 5G NR roadmap in 3GPP Release 16 and beyond", September 2018.

[9] Nokia, "Completing the 5G Vision – Industry Roadmap", EUCNC2019, June 2019, Valencia.

[10] IEEE 802, "IEEE 802.11 Overview and Completed Amendments", April 2019, http://www.ieee802.org/.

[11] ITU-R IMT-2020 "Minimum Technical Performance Requirements for IMT2020 radio interfaces", https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Documents/S01-1_Requirements%20for%20IMT-2020_Rev.pdf

[12] 3GPP TR 37.910 "Study on self-evaluation towards IMT-2020 submission", 14 October 2019, https://itectec.com/archive/3gpp-specification-tr-37-910/

[13] 3GPP TR 37.910 "Study on self-evaluation towards IMT-2020 submission", 14 October 2019, https://itectec.com/archive/3gpp-specification-tr-37-910/

[14] Thomas Kürner (2018). Turning THz Communications into Reality: Status on Technology, Standardization, and Regulation. http://doi.org/10.1109/IRMMW-THz.2018.8510153

[15] Thomas Kürner (2019). Regulatory Aspects of THz Communications and related Activities towards WRC 2019. European Conference on Networks and Communications (EUCNC2019), Valencia, Spain 18-21 June 2019

[16] 3GPP "RAN Rel-16 progress and Rel-17 potential work areas", https://www.3gpp.org/news-events/2058-ran-rel-16-progress-and-rel-17-potential-work-areas

[17] Erik Dahlman et al., "Artificial Intelligence in Future Evolution of Mobile Communication", 2019 International Conference on Artificial Intelligence in Information and Communication (ICAIIC)

[18] O. Simeone, "A very brief introduction to machine learning with applications to communication systems," IEEE Transactions on Cognitive Communications and Networking, vol. 4, no. 4, pp. 648–664, 2018.