

Article

A Baseline Roadmap for Advanced Wireless Research Beyond 5G

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Abstract: This paper presents a baseline roadmap for the evolution of 5G new radio over the next decade. Three timescales are considered, namely short-term (2022-ish), medium-term (2025-ish), and long-term (2030-ish). The evolution of the target key performance indicators (KPIs) is first analyzed by accounting for forecasts on the emerging use cases and their requirements, together with assumptions on the pace of technology advancements. The baseline roadmap is derived next by capturing the top-10 and next the top-5 technology trends envisioned to bring significant added value at each timescale. Being intrinsically predictive, our proposed baseline roadmap cannot assert with certainty the values of the target KPIs and the shortlisting of the technology trends. It is, however, aimed at driving discussions and collecting feedback from the wireless research community for future tuning and refinement as the 5G evolution journey progresses.

Keywords: 5G; 3GPP; wireless; KPI; roadmap

1. 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 has 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 its focus upon the longer-term 6G research with a 10 years' time-horizon towards 2030, the industry R&D stakeholders are rather focusing on the short to medium term enhancements of the current 5G system specifications with up to a 5 years' time-horizon.

The H2020 EMPOWER project [1] is an initiative launched recently (November 2018) in Europe with the aim of capturing the trends and advancements in wireless research, including experimental tools for B5G systems. This paper presents the first results from EMPOWER towards a comprehensive advanced wireless technology roadmap for the shorter, medium and longer term evolution of 5G. The methodology adopted to develop the roadmap follows the proven Semiconductor Industry Roadmap process presented in [2]. This methodology consists of three phases: (1) preliminary activity, (2) development of the technology roadmap, and (3) follow-up activity. The preliminary activity includes: (i) Identify the need/use of the roadmap; and (ii) Define the scope and boundaries of the technology roadmap.

The development of the technology roadmap includes: (i) Specify the major technology areas; (ii) Determine the critical system requirements and their targets; (iii) Specify major technical solutions pertinent to the target KPIs, including alternatives and timelines; (iv) Roadmap the technical solutions towards targets; and (v) Issue recommendations on areas of priority including analysis of risks. The Follow-up activity includes: (i) Critique and validate the roadmap; (ii) Develop an implementation plan; and (iii) Review and update. As reported by the authors in [2], this process has been followed by several global Semi-Conductor companies with R&D as a major product.

In this paper, we present results of our work corresponding to the preliminary activity and the development of the technology roadmap phases of the roadmap process. The Follow-up activity process is left for future dissemination. In our preliminary activity phase, the roadmap scope is set on wireless technology advances that are pertinent to the evolution of 5G new radio (NR) over the next decade 2020–2030. In our development of the technology roadmap phase, we identified five technology areas that will influence the 5G evolution towards 6G. These are: (i) Circuits and devices; (ii) Radio transceivers; (iii) Radio systems; (iv) Network protocols; and (v) Data and intelligence. With the aim to focus our efforts in this paper, we elected to focus on the areas of radio system and transceivers which are typically the area of focus of ITU-R IMT (International Mobile Telecommunications) systems. This is anticipated to provide a comprehensive roadmap, consolidating the views from the radio research community, 3GPP and IEEE 802 standards, and radio spectrum forums. The contribution of this paper is the product of an in-depth analysis of current literature on Beyond 5G roadmaps published or presented by several research forums (e.g., WWRF, NetWorld2020, H2020 5G-PPP, 6G-Summit, USA NSF), industry organizations (e.g., 3GPP, IEEE, ETSI, ITU-R, ITU-T), and spectrum regulatory forums (e.g., FCC, ECC, OFCOM, WRC'19), such as the ones presented in [3–24].

The rest of this paper is organized as follows: Section 2 starts with capturing emerging use cases and their requirements; Section 3 next provides our forecasts of the target KPIs evolution in the short, medium and long-term evolutions of 5G; Section 4 follows with key technology trends envisioned to meet the target KPIs; Our conclusions and next steps are presented in a final Section 5.

2. 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, enhanced mobile broadband (eMBB), ultra-reliable and low latency communication (URLLC), and massive machine type communication (mMTC).

2.1. 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 [25–27]. The most consuming user applications in 2024 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 (1920 × 1080); (ii) 360° Video—720p HD; (iii) Virtual Reality (VR) Full HD; and 4K UHD (3840 × 2160). 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 (7680 × 4320); and (ii) Volumetric media streaming.

This forecast gives therefore an increase in user traffic of approximately five 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.

2.2. Forecasts in the Industry Verticals Space

The industry verticals space is one of the main differences between 5G and B5G, compared to previous generations. Various forums such as 5G Automotive Association (5GAA) [28] and the 5G Alliance for Connected Industries and Automation (5GACIA) [29], have already been active in defining their use cases and requirements, and channeling these into 5G standardization development organizations, primarily Third Generation Partnership Project (3GPP) [30]. This is clearly evidenced in 3GPP 5G specifications through the enhancements of cellular V2X and the introduction of NR-light to 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. Taking manufacturing as an example of the vertical domain, which is forecast in 2026 to be one of the largest and fastest growing market for 5G and its evolution [31,32], there are several use cases which require different combinations of the 5G eMBB and URLLC services. To appreciate the diverse requirements in the manufacturing use cases, Table 1 provides a sample of the KPI requirements extracted from [31,32]. As reported in [31], 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.

Table 1. Sample of key performance indicator (KPI) requirements from the manufacturing vertical use cases [31,32].

KPI	Requirement
Data rate	Up to several Gbps
End-to-End latency	Varies from 0.5 ms to 500 ms
Time synchronicity	Down to 1 us
Reliability/Availability	Varies from 3 nines up to 8 nines
Positioning	Varies from 0.2 m to 10 m

3. B5G Target KPIs Evolution

Table 2 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) [33,34]. This is also illustrated in a graphical representation in Figure 1, where the evolution of KPIs relating to spectrum and density is depicted in a first diagram on the left, and the evolution of the remaining KPIs including reliability, latency, energy efficiency, mobility and positioning accuracy depicted in a second diagram on the right. 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 of these KPIs are not new, but their target values are envisioned to evolve in the various phases of the evolution of 5G.

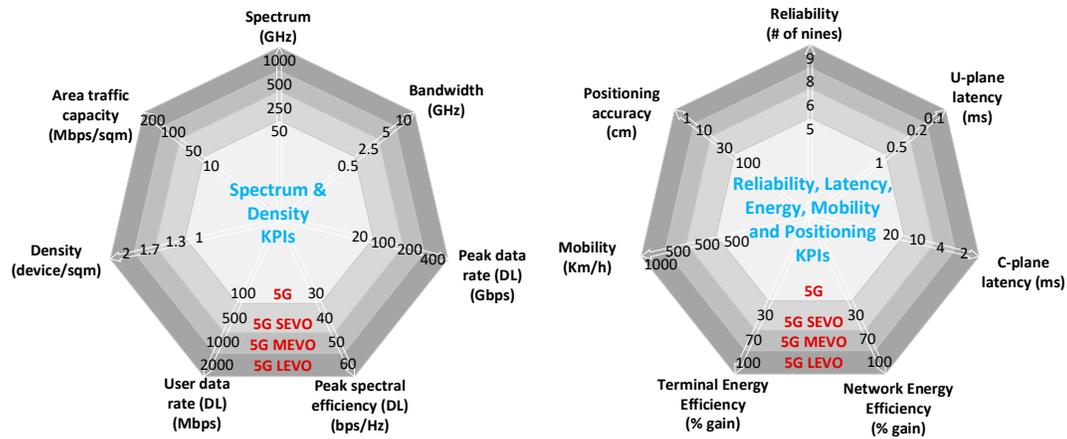


Figure 1. Evolution of targeted KPIs for the short, medium, and long-term evolution of 5G new radio (NR).

Table 2. Targeted KPIs for the short, medium, and long-term evolution of 5G NR.

Target KPI	Target in 5G	Target in 5G SEVO	Target in 5G MEVO	Target in 5G 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

3.1. Spectrum and Bandwidth

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 has not been yet an agreement on the new cap going forward, whether it will be for example 100 GHz or 250 GHz. We therefore set the target threshold of the spectrum in SEVO (Rel-17, 18, 19) 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 [5,6,13,14].

Bandwidth: The bandwidth was derived in accordance with the Spectrum KPI, and it represents a single channel bandwidth, and thus it does not include any aggregation. Today in 3GPP 5G NR, the channel bandwidth may go up to 0.5 GHz range (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 ($\approx 52.6/0.5 \approx 250/2.5 \approx 500/5 \approx 1000/10$). 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.

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

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 the 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.

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 2.1 for the end user video streaming applications and some of the exemplary manufacturing use cases in Section 2.2.

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.

3.3. Density and Area Traffic Capacity

Density: The evolution of the density from today's 5G target of one 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 UAV market is expected to be significantly smaller in terms of the number of devices (e.g., <10 M units annual by 2026 according to ABI research). Based on recent forecasts [25], around 37 billion connected devices are forecast by 2025, of which about 25 billion will be related to the Internet of Things (IoT). Connected IoT devices include connected cars, machines, sensors, consumer electronics and wearables. The forecast in [25] 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.

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 5G short-term, medium-term and long-term evolutions.

3.4. Reliability and Latency

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 up to 9 nines in the long term. This prediction aligns with the requirements outlined in Section 2.2 for exemplary manufacturing use cases and also tactile services from [35], where a reliability target of 9 nines is already set for services like telesurgery.

U-plane latency: Today in 5G NR, the URLLC target for U-plane latency is 1 ms. 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 and tactile Internet services from [35]. For 5G NR MEVO, we assumed a further reduction down to 0.2 ms in line with the forecasted increase in channel bandwidth (thus a 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 distances. It is noteworthy however that the authors of this paper are not aware at present of emerging use cases or services yet that would require U-plane latency below 0.5 ms. Therefore, these forecasted KPIs of 0.2 ms and 0.1 ms in the next 5–10 years are purely based on a technical forecast rather than a present use case requirement.

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 is less than 20 ms and encouraged to go below 10 ms when the U-plane latency target is 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 envision 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).

3.5. Energy Efficiency

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.

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, energy harvesting, wireless power transfer, etc.

3.6. Mobility

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 traveling in excess of 500 Km/h (e.g., UAVs, airplanes) which might need to be supported, hence the target of 1000 Km/h is forecast for 5G LEVO.

3.7. Positioning Accuracy

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 the evolution of 5G will ultimately in the long-run try to achieve this cm-level accuracy, mainly thanks to a higher spectrum with integrated sensing and communication, and the integration of non-terrestrial networks (e.g., satellites), which already achieves today cm-level positioning accuracy. The target accuracy is therefore envisioned to improve to below 30 cm, 10 cm and 1 cm, in 5G SEVO, MEVO and LEVO, respectively.

4. Technology Trends and Baseline Roadmap

Table 3 provides a shortlist of top 10 wireless technology trends, for the short, medium and long-term evolution of 5G (SEVO, MEVO, LEVO). A baseline roadmap is then depicted in Figure 2 based on a further shortlisting to the top 5 technology trends for each 5G evolution phase. This is also benchmarked with the top 5 technologies in current 3GPP 5G NR, based on releases Rel-15 and Rel-16. The timeline of future 3GPP releases in Figure 2 is merely speculative. The shortlisting of the top five technologies to appear in the baseline roadmap is based on a qualitative assessment of the added value envisioned for a given technology trend compared to previous B5G phases.

Table 3. Wireless technology trends for 5G SEVO, MEVO and LEVO.

No	5G SEVO Trends—Top 10	5G MEVO Tre—Top 10	5G LEVO Tre—Top 10
1	Transmission schemes at mmWave frequencies above 52.6 GHz up to 250 GHz	Transmission schemes at mmWave frequencies above 250 GHz up to 500 GHz	Transmission schemes at mmWave frequencies above 500 GHz up to 1 THz
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 (Holographic MIMO)
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 802.11 and 802.15) [36,37]. 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. 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, the maturity of which 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.

In the sequel, and for the sake of brevity, we have selected only four exemplary technologies which are envisioned to continuously evolve over the next decade. These are: (i) Sub-THz spectrum, (ii) Integrated access and backhaul, (iii) Massive LEO satellites and HAPs, and (iv) Wireless AI fusion. Other technologies listed in Table 3 and included in the baseline roadmap in Figure 2 are equally important and envisioned to also continuously evolve in B5G. The four technologies selected below are only presented as representative examples of the full list of technology trends in Table 3 and in Figure 2. The detailed description of each technology trend in Table 3 and in Figure 2 and its mapping to the target KPIs from Section 3 above is left for future work.

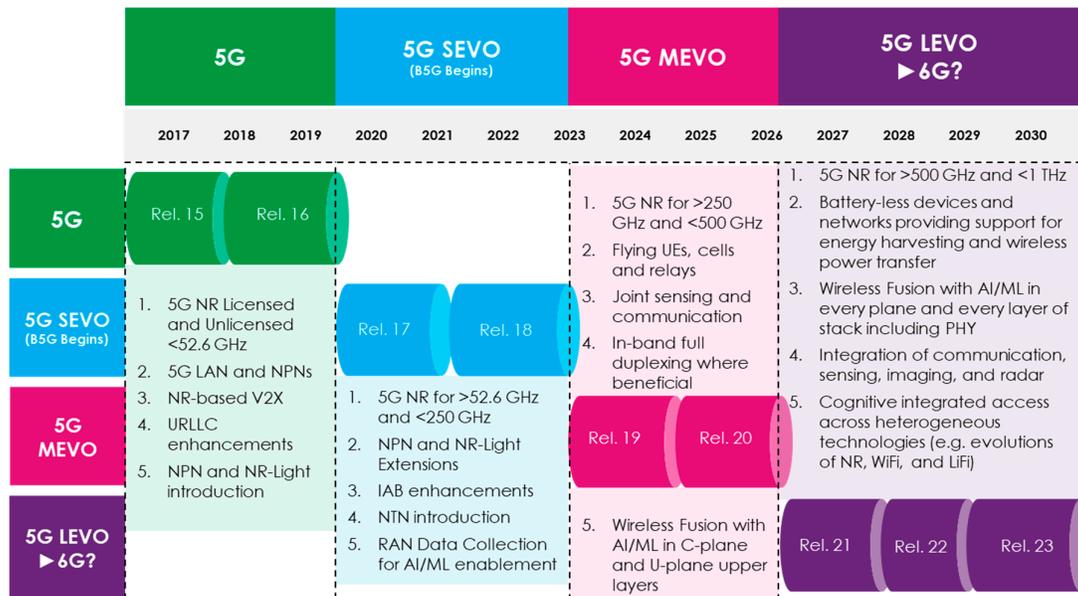


Figure 2. Baseline Technology Roadmap from a 3GPP-Release viewpoint.

4.1. Sub-THz Spectrum

The spectrum is a key asset for evolving wireless technologies and services, and it is expected that the upper spectrum boundaries will be pushed further towards THz frequencies. Currently, bands up to 52.6 GHz are identified for IMT2020 (5G). The need for a new spectrum is obvious, as the visions and requirements for data rates are constantly being more demanding. Increasing the amount of available spectrum is, together with network densifications, the most important way of providing more network capacity and data rates for users and use cases. More spectrum addresses several KPIs. Peak and user data rates will increase, thanks to the added bandwidth. Pushing spectrum to higher frequencies will also enable tighter reuse distances (smaller cells), supporting increasing devices densities, as well as area traffic capacity.

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 has not been yet an agreement on the new cap, whether it will be for example 100 GHz or 250 GHz. In front of ITU-R World Radio Conference (WRC) 2019, a compatibility study for the frequency range 275–450 GHz has been performed, for studying the coexistence of fixed services, land mobile services and radio astronomy services [5,6]. Parts of this range will most likely be identified as future IMT-bands, supporting our MEVO target. The position of regulators such as CEPT is to protect the so-called passive services in this band.

Several vertical-based applications will benefit from accurate positioning, as outlined in Section 2.2. In 3GPP 5G NR Rel-16, positioning accuracy has started to be addressed. The forthcoming Rel-17, planned for Q2/2021, will enhance this further with cm level accuracy (factory/campus positioning, IoT, V2X positioning, 3D positioning), as well as latency and reliability improvements [36]. Currently different 4G LTE positioning methods are being brought into 5G, using uplink and downlink signals to determine device positions relative to mobile network antennas. Examples are enhanced Cell-ID and TDOA-based approaches. Moving to new, higher frequencies affects the density of access points and base stations. In addition, the introduction of antenna arrays with beamforming capabilities will help to direct signals towards end users. This will improve the resolution of multipath components improving positioning performance. Additionally, it may become possible to localize devices using a single base station. Single approaches will not be able to reliably provide the accuracy required by the target use cases in all environmental conditions. Hybrid solutions that optimally combine multiple cellular approaches with non-cellular ones, such as GNSS, terrestrial beacon systems (TBS), measurements based on Wi-Fi and Bluetooth, and inertial measurements (IMU), are most promising to achieve the goals.

Consequently, the 3GPP study scope includes GNSS and satellite signals, as well as terrestrial signals, such as Wi-Fi and Bluetooth, and more.

4.2. Integrated Access and Backhaul

The basic function of Integrated Access and Backhaul (IAB) is to enable flexible, re-configurable and cost-effective network architectures by using wireless backhaul links to relay and control the access traffic. One of the key factors for IAB becoming more important in 5G compared to earlier generations is that the deployment of network nodes in 5G is expected to be significantly denser and more dynamic, especially when operating in high frequency bands. Since Rel-15, 3GPP has studied feasibility and techniques for IAB. The study includes multiple architectures and requirements for several basic critical use cases. In future Rel-17, 3GPP is set to continue to explore new IAB use cases and to specify further enhancements.

The possible use cases may include a high-speed train scenario (e.g., the mobile IAB-node is installed on a high speed train and serves the UEs inside the train), a mobile base station (e.g., moving base station as urban cell site such as taxis, buses, subway), HAPS/satellites (e.g., using NGSO satellite constellation as backhaul network for large coverage), an ad-hoc network with temporary or semi-permanent IAB for slow moving node deployment), and the extension of the IAB functionalities into the unlicensed band. The possible enhancements may include duplexing, topology adaptation and topology and routing enhancements, network coding, enhancements to reduce signaling latency over backhaul, enhancement for real time services, enhancement to end-to-end flow control to reduce buffering in the IAB network, IAB node energy saving, etc. These proposed enhancements aim to reduce backhaul latency, manage interferences, enhance system spectral and operational efficiencies, control traffic blockage and congestion in various link topologies, and mitigating link failure impact.

It is worth mentioning that the development and enhancement of IAB have never been separated from the development and enhancement of other features of the wireless system. As more flexible and dynamic network architectures are introduced to support a wide variety of use cases in ever-dense deployment, different layers of the system are required to be upgraded as well. For example, to enable low latency backhaul, network coding and duplexing, significant PHY and MAC enhancements may be required. The IAB enhancements are therefore set to evolve all along the journey of 5G evolution from the short term in Rel-17 all the way up to the long term including 6G.

4.3. 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 B5G.

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 m. 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 also anticipated to be deployed more widely and in higher density, and enhanced by advances in manufacturing, drones, energy and artificial intelligence. HAPs are therefore also positioned to become a key infrastructure element in the architecture and deployment of B5G.

The 3GPP in its Rel-15 and Rel-16 has already started to study the integration of non-terrestrial networks (NTNs). This activity is set to continue in the upcoming Rel-17, and will be further amplified in future Rel-18 and beyond, including the deployment of massive NTN infrastructures such as VLEOs and HAPs.

4.4. Wireless AI Fusion

Artificial Intelligence (AI) is widely tipped to be a disrupting technology that will impact the design of the B5G wireless system by improving some of the existing KPIs (e.g., positioning accuracy and energy efficiency) and eventually introducing new KPIs. Today researchers have demonstrated numerous examples of successfully applying 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 the long term, 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 of the data and intelligence that is pervasively distributed across the continuum from the terminal to the edge and Cloud, and (iii) mitigate data privacy and reduce network latency. Wireless AI fusion 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.

Today, Wireless AI fusion technologies are especially successful at detecting and recognizing patterns within complex data streams at all layers of the protocol stack, even when the information of interest is not explicitly encoded in the packets (see [7,8]). This information can be used for various aspects in current wireless system design and operation, including: (i) filtering of irrelevant or untrusted streams, (ii) controlling the operation of the RAN or a communication protocol, or (iii) modifying the behavior of a connected station so that the network operation improves.

In 3GPP Rel-16, a first manifestation of the wireless AI fusion occurred through the introduction of the data analytics framework in the 5G system architecture. This framework is being enhanced today for future 3GPP releases and is envisioned to continue to be enhanced further to impact, not only the core network, but also the RAN, and the UE. In the short-term evolution of 5G, the focus is set on the mechanisms for data collection and exposure from all entities of the wireless system, including UE, RAN and Core. In the medium term, we envision the wireless system to make use of the available data exposed from all entities in the network to drive end-to-end system design optimization in the C-plane and upper layers of the U-plane. This is especially as these mechanisms are more delay-tolerant than in the lower layers of the U-plane. Ultimately, with the future advancements envisioned in computational speed, lower complexity learning algorithms, and algorithms which are more tailored to the wireless system design needs, we envision the future wireless system to become AI-native where AI is pervasive in every layer of the protocol stack equally in the C-plane and U-plane, including in the lower time-sensitive layers, such as the physical layer.

5. Conclusions and Next Steps

This paper presented a baseline roadmap for the evolution of 5G new radio in the short, medium and long terms towards 2030. An evolution of the target KPIs was first presented based on forecasts for the requirements from emerging use cases and on the pace of technological advance. This was followed next by capturing the top-10 wireless technology trends in each phase of 5G evolution. These were then further shortlisted to top-5 trends in each phase and mapped onto a speculative timeline of future 3GPP releases from Rel-17 onwards. Next, we selected four exemplary technologies and elaborated on their evolution journey from the short to the long term, primarily from a 3GPP perspective. These included: (i) Sub-THz spectrum, (ii) Integrated access and backhaul, (iii) massive VLEOs and HAPs, and (iv) wireless AI fusion.

The details of which target KPIs are enabled by which technology trend, and what are the anticipated gains, trade-offs and maturity timelines, is an ongoing work by the authors for future dissemination. Being predictive in nature, the authors acknowledge that this baseline roadmap may be missing some KPIs (e.g., relating to future applications that cannot be imagined yet), and some future technology trends or breakthroughs which have not yet emerged. These hypothetically missing KPIs and trends will be captured as they emerge in future releases of the baseline roadmap.

Author Contributions: A. M. has led the overall development of the baseline roadmap with focus on KPIs forecast and technology trends taken primarily from future 3GPP releases viewpoint. He also led on the massive LEOs and HAPs technology trend. R.Y. has contributed towards the development of the baseline roadmap with focus on KPIs forecast and technology trends taken from future IEEE 802.11 and IEEE 802.15 activities' viewpoint. He also led on the integrated access and backhaul technology trend. P.H.L. has contributed towards the development of the baseline roadmap with focus on sub-THz spectrum trends. A.d.l.O. has contributed towards the development of the baseline roadmap with focus on the technology trends relating to wireless-AI fusion. All authors have read and agreed to the published version of the manuscript.

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References

1. EMPOWER. Available online: <https://www.advancedwireless.eu/> (accessed on 15 November 2019).
2. Garcia, M.L.; Bray, O.H. *Fundamentals of Technology Roadmapping*; Sandia National Laboratories: Livermore, CA, USA, 1997.
3. Qualcomm. Expanding the 5G NR Ecosystem—5G NR Roadmap in 3GPP Release 16 and Beyond. Available online: <https://www.qualcomm.com/media/documents/files/expanding-the-5g-nr-ecosystem-and-roadmap-in-3gpp-rel-16-beyond.pdf> (accessed on 15 November 2019).
4. Nokia. Completing the 5G Vision—Industry Roadmap. In Proceedings of IEEE EUCNC, Valencia, Spain, 17–21 June 2019.
5. Thomas Kürner. Turning THz Communications into Reality: Status on Technology, Standardization, and Regulation. 2018. Available online: <http://doi.org/10.1109/IRMMW-THz.2018.8510153> (accessed on 15 November 2019).
6. Thomas Kürner. Regulatory Aspects of THz Communications and related Activities towards WRC 2019. In Proceedings of the European Conference on Networks and Communications (EUCNC2019), Valencia, Spain, 18–21 June 2019.
7. Dahlman, E.; Parkvall, S.; Peisa, J.; Tullberg, H.; Murai, H.; Fujioka, M. Artificial Intelligence in Future Evolution of Mobile Communication. In Proceedings of the 2019 International Conference on Artificial Intelligence in Information and Communication (ICAIIIC), Okinawa, Japan, 11–13 February 2019.
8. Simeone, O. A very brief introduction to machine learning with applications to communication systems. *IEEE Trans. Cognit. Commun. Netw.* **2018**, *4*, 648–664.
9. NetworkWorld2020. Smart Networks in the Context of NGI. 2018. Available online: <https://www.networkworld2020.eu/wp-content/uploads/2018/11/networkworld2020-5gia-sria-version-2.0.pdf> (accessed on 15 November 2019).
10. NetworkWorld2020. Conclusions from Visions for Future Communications Summit—Futurecomms Summit, Version: 1.0. 2017. Available online: <https://www.futurecomresearch.eu> (accessed on 18 February 2020).
11. 5G PPP. View on 5G Architecture, Version 3.0. 2019. Available online: <https://5g-ppp.eu/white-papers/> (accessed on 15 November 2019).
12. IEEE Future Networks. IEEE 5G and Beyond Technology Roadmap White Paper. Available online: <https://www.futurenetworks.ieee.org/roadmap> (accessed on 15 November 2019).
13. Kurner, T. IEEE 802.15.3d and other activities related to THz Communications. Where to go next? In *Towards Terahertz Communications Workshop*; European Commission: Brussels, Belgium, 2018.
14. Rappaport, T.S.; Xing, Y.; Kanhere, O.; Ju, S.; Madanayake, A.; Mandal, S.; Alkhateeb, A.; Trichopoulos, G.C. Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond, *IEEE Access* **2019**, *7*, 78729–78757.
15. Saad, W.; Bennis, M.; Chen, M. A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems. 2019. Available online: <https://arxiv.org/abs/1902.10265> (accessed on 15 November 2019).
16. Tariq, F.; Khandaker, M.; Wong, K.K.; Imran, M.; Bennis, M.; Debbah, M. A Speculative Study on 6G. Available online: <https://arxiv.org/abs/1902.06700> (accessed on 15 November 2019).

17. Chen, W.; Shi, Y.; Zhang, J.; Zhang, Y.J. The Roadmap to 6G—AI Empowered Wireless Networks. Available online: https://www.researchgate.net/publication/332726164_The_Roadmap_to_6G_-_AI_Empowered_Wireless_Networks (accessed on 15 November 2019).
18. ITRS 2.0. International Technology Roadmap for Semiconductors 2.0. 2015. Available online: <http://www.itrs2.net/> (accessed on 15 November 2019).
19. ITU-R. CPM Report on technical, operational and regulatory/procedural matters to be considered by the World Radiocommunication Conference 2019. In Proceedings of the 2nd Session of the Conference Preparatory Meeting for WRC-19, Geneva, Switzerland, 18–28 February 2019.
20. ECC Report 80. Enhancing Harmonisation and Introducing Flexibility in the Spectrum Regulatory Framework. Available online: <https://www.ecodocdb.dk/download/f651b5d9-21ab/ECCREP080.PDF> (accessed on 15 November 2019).
21. Ofcom. Licence-Exemption Framework Review. 2007. Available online: https://www.ofcom.org.uk/__data/assets/pdf_file/0015/41280/lefr_statement.pdf (accessed on 15 November 2019).
22. Holland, O.; Bogucka, H.; Medeisis, A. *Opportunistic Spectrum Sharing and White Space Access: The Practical Reality*; Wiley Telecom: 2015. Available online: <https://ieeexplore.ieee.org/servlet/opac?bknumber=8040141> (accessed on 15 November 2019).
23. Ofcom. Enabling Opportunities for Innovation. Shared Access to Spectrum Supporting Mobile Technology. 2018. Available online: https://www.ofcom.org.uk/__data/assets/pdf_file/0022/130747/Enabling-opportunities-for-innovation.pdf (accessed on 15 November 2019).
24. Bundesnetzagentur. Bundesnetzagentur veröffentlicht Rahmenbedingungen für lokale 5G-Anwendungen. 2019. Available online: https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2019/20190311_LokaleFrequenzen.html (accessed on 15 November 2019).
25. Ericsson Mobility Visualizer. Available online: <https://www.ericsson.com/en/mobility-report/mobility-visualizer> (accessed on 15 November 2019).
26. Ericsson Mobility Report. 2019. Available online: <https://www.ericsson.com/assets/local/mobility-report/documents/2019/ericsson-mobility-report-june-2019.pdf> (accessed on 15 November 2019).
27. Cisco Visual Networking Index. Global Mobile Data Traffic Forecast Update, 2017–2022. 2019. Available online: <https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-738429.html> (accessed on 15 November 2019).
28. 5G Automotive Association (5GAA). Available online: <https://www.5gaa.org> (accessed on 15 November 2019).
29. 5G Alliance for Connected Industries and Automation (5GACIA). Available online: <https://www.5g-acia.org> (accessed on 15 November 2019).
30. Third Generation Partnership Project (3GPP). Available online: <https://www.3gpp.org> (accessed on 15 November 2019).
31. 5GACIA. 5G for Connected Industries and Automation. Available online: <https://www.5g-acia.org/publications/5g-for-connected-industries-and-automation-white-paper/> (accessed on 15 November 2019).
32. 5GACIA. 5G for Automation in Industry. Available online: <https://www.5g-acia.org/publications/5g-for-automation-in-industry-white-paper/> (accessed on 15 November 2019).
33. 3GPP TR 37.910. Study on Self-Evaluation Towards IMT-2020 Submission. Available online: <https://itectec.com/archive/3gpp-specification-tr-37-910/> (accessed on 14 October 2019).
34. ITU-R IMT-2020. Minimum Technical Performance Requirements for IMT2020 Radio Interfaces. Available online: https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Documents/S01-1_Requirements%20for%20IMT-2020_Rev.pdf (accessed on 15 November 2019).
35. Kim, K.S.; Kim, D.K.; Chae, C.; Choi, S.; Ko, Y.; Kim, J.; Lim, Y.; Yang, M.; Kim, S.; Lim, B.; et al. Ultrareliable and low-latency communication techniques for tactile internet services. *Proc. IEEE* **2019**, *107*, 376–393.

36. 3GPP. RAN Rel-16 Progress and Rel-17 Potential Work Areas. Available online: <https://www.3gpp.org/news-events/2058-ran-rel-16-progress-and-rel-17-potential-work-areas> (accessed on 15 November 2019).
37. IEEE 802. IEEE 802.11 Overview and Completed Amendments. 2019. Available online: <http://www.ieee802.org/> (accessed on 15 November 2019).



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