From Lessons Learned in 5G to Innovative Solutions in 6G

A white paper established by Working Group Innovation Management

November 2025

This is a preprint version of the white paper. Minor adaptations, including content corrections, editorial revisions, or design changes, may appear in the final published version.

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Contents

Executive Summary

This whitepaper documents a systematic exploration of the challenges that were encountered in the industrial deployment of 5th generation of cellular networks (5G), the lessons learned from non-public network (NPN) deployments, and a set of actionable design principles for the 6th generation of cellular networks (6G). Based on a survey of experts, review of literature, standards, and real world deployments, the analysis focuses on four critical aspects: technological, economic, standardisation, and regulatory.

Research and survey findings indicate that the successful implementation of 6G requires a balanced approach across these critical aspects. Technologically, advanced solutions such as modular architectures and artificial intelligence (AI) -driven tools are essential for improving performance and ease of operation. Economically, strategies such as backward compatibility are critical to controlling costs. From a standardisation perspective, a clear industry roadmap and closer coordination between standardisation bodies and implementers are necessary to prevent late product roadmaps. Finally, regulatory frameworks must be updated to address spectrum allocation and cross-border compatibility, paving the way for the smooth global rollout of 6G in industrial and professional deployments.

The paper concludes that the main bottlenecks for the adoption of cellular networks are the high deployment cost, complex configuration, and the fact that the implementation of required functions are still unavailable. It also proposes a list of innovative solutions to address these issues. Some examples include backward-compatible network architectures, which are suggested to decrease costs. AI-driven configuration tools and user-friendly interfaces are suggested to ease complex configuration. Open industry-wide standards and thorough testing are suggested to mitigate interoperability issues. Moreover, detailed reasons are given for the function implementations that are not yet available, so that these gaps can be addressed as well.

1 Introduction and motivation

Cellular networks are gaining attention in adoption of internet of things (IoT) devices due to the mobility, scalability and wide coverage. However, since Long-Term Evolution (LTE) was introduced, several obstacles from high infrastructure costs to security concerns were revealed. These obstacles slowed widespread acceptance of cellular networks in industry even to the current rollout of 5G. By investigating the use cases from industry, this white paper identifies valuable lessons regarding the gaps causing this impediment. As we move forward to 6G, it is crucial to draw on past experiences and mitigate the potential risks such as cost and operational challenges. This awareness enables innovative solutions such as customized network architecture and AI-driven network orchestration.

NPNs utilizing 5G technology have been rolled out in many test scenarios in industry and for research of industrial applications. However, the commercial use of these industrial 5G use cases remains limited. Private networks correspond to one option of NPN deployment [1]. Knowledge and experience have been collected in many of these NPN deployments. And they are instrumental in discovering which challenges presented themselves, both those that have been resolved and those yet to be resolved. Many lessons can be learned from these deployments and must be used to improve the uptake of 5G, the 5G technology itself, and the future mobile cellular networks like 6G. Much of this knowledge was gathered through deep-dives in literature and personal correspondence with the stakeholders in different deployments, as well as from different conferences and summits, such as the Industrial Radio Day, 6G Conference, and IEEE 6G Summit, where seminal lectures, riveting panel discussions, and intense discussions occurred.

The motivation behind this white paper is threefold. The first point is the collection, consolidation, and publishing of the knowledge and experiences gathered, so that all can benefit from it. The second point is to gain the perspective of different stakeholders about the challenges and lessons learned by conducting a survey. The results of the survey will help to demonstrate which of these challenges and lessons learned are most important to focus on, so that the adoption and success of innovative ideas in 6G can be facilitated. The final point is to present innovative ideas for 6G based on the collected challenges and lessons learned as well as the survey results to the appropriate stakeholders to improve the development of the future cellular technology. The remainder of the white paper is structured as follows: Section 2 describes the survey in more detail and discusses how it was designed and analysed. Sections 3 and 4 discuss the challenges of 5G and the lessons learned. Section 5 discusses potential innovative solutions to these challenges. Finally, Section 6 introduces recommendations and concludes the paper.

2 Methodology

This section describes the methods used to design the survey, collect the data, and analyse the results.

2.1 Survey Design and Objectives

The survey was designed to achieve the following objectives:

- Identify key challenges associated with the adoption of 5G networks in industry.
- Gather lessons learned from past experiences with 5G network planning, deployment, and functionalities.
- Explore potential solutions and innovations for addressing these challenges in 6G networks.

The questions were designed to cover the technological, economic, standardisation, and regulatory aspects of the cellular networks. The survey included quantitative questions such as Likert scale, multiple choice and ranking question, and qualitative questions as open-text to gather detailed insights when needed.

2.2 Data Collection and Population

The survey was distributed via the mailing list of working group 3 "Innovation Management" of the 6G Platform. The members of working group 3 and other participants also distributed the survey through their professional networks. The survey was active for two weeks, and received a total of 18 responses. Only considering the number of people who received a personalised invitation, the response rate was 45 %. The survey targeted a diverse range of stakeholders. Figure 1 shows the number of participants in each category. However, not all targeted categories were represented in the final responses. Below, we provide a brief description of the categories included in the survey results.

- Mobile Network Operator (MNO): Telecommunication companies providing cellular communication and supplying the necessary network infrastructure.
- Enterprise (End user): Companies utilizing 5G technology for use cases and applications.
- Service Vendor: Companies which develop, integrate, and sell equipment, devices, and services for utilizing 5G technology.
- Industry association: Associations and organizations, which bring together different stakeholders to push for the best circumstances for industry.

The participants who selected the "Other" option specified their categories as Test & Measurement, Research, Hardware Vendor, Technology Provider and Test Equipment Vendor. One of them did not specify the category.

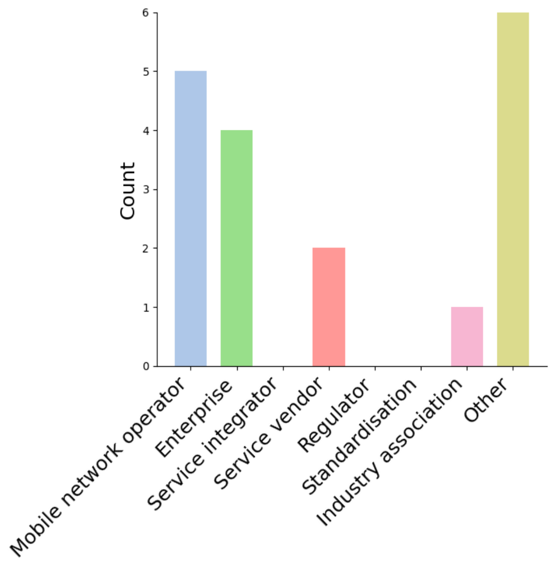

Figure 1: Distribution of participants by category.

2.3 Data analysis

After completion of the survey, the results were analysed to determine their significance. For most questions in the survey, the participant could choose any of the answers given, including a "no answer" option, if they felt that they did not have enough information to answer the question. The results of the survey questions were calculated without consideration of "no answers". Consequently, percentages and other calculation only take into account the participants who answered the questions.

2.3.1 Calculation of Likert mean values

In some cases, a mean value was useful for comparing the results of different, but related questions, which all utilized the same Likert scale. The Likert scale was: strongly agree, agree, neutral, disagree, and strongly disagree. The results were mapped to the following values: strongly agree = 2, agree = 1, neutral = 0, disagree = -1, and strongly disagree = -2. The mapped values were used to find a mean of all answers to the specific question.

2.3.2 Calculation of weighted average by ranking question

The survey included one ranking question which is discussed in Section 5. Participants could rate each category from 1 (most important) to 5 (not important at all). Not all participants rated every category. To account for this, the weighted rating was first calculated for each category based on the number of responses for that specific category, followed by an average relative to the total number of 18 participants. Additionally, for visual reasons the ranking was also reversed in the results to 5 (most important) and 1 (not important at all).

2.3.3 Multi-select questions

There were a number of multiple-choice questions, where several options could be selected. These questions are called multi-select questions. It is important to mention that during the analysis of these questions when calculating the percentages, the totals exceed 100 %.

2.4 Ethical Considerations

The survey was designed to ensure anonymity of the participants.

3 Challenges faced in 5G

During the roll-out of 5G solutions and the implementation of 5G use cases, diverse challenges were experienced. Some challenges were resolved and overcome, while others are still being faced. Both should be documented so the same challenges can be avoided in the next generation of mobile technology and the solutions to the ongoing challenges can be found. This white paper groups the challenges in four main categories: technological, economic, standardisation, and regulatory challenges. These are presented in the following sections. The challenges outlined were gathered first via correspondence with different stakeholders as described in the introduction. Most challenges were then included in the survey described in Section 2 to get an idea of the current state of the challenges based on the opinion of different stakeholders in the industry. Moreover, the survey results are presented in this section.

3.1 Technological challenges

In many cases, utilizing the technology itself comes with its own challenges. In this section, challenges related to performance, to deployment and implementation, and to security and resilience are included.

3.1.1 Performance related challenges

Many challenges regarding the performance of the 5G solutions arise from the real-time requirements of many industrial use cases. These use cases require an extremely high reliability [2]. Furthermore, the high reliability is often required in combination with keeping the transmission time low even with complex channel coding [2]. These reliability and timing requirements fall under the umbrella of the 5G service ultra-reliable low latency communication (URLLC). Currently, commercial 5G systems do not meet the timing requirements of all URLLC use cases, due to various factors like hybrid automatic repeat request (HARQ) retransmissions and processing delays, which influence the deterministic behavior. When asked about this subject in the survey, a majority of the participants agreed, 69 %, that it is a critical issue that current commercial 5G deployments do not meet the requirements specified by the 3rd Generation Partnership Project (3GPP) for URLLC, which should deliver 1 ms end-to-end latency with 99.999 % reliability. Even though many industrial use cases do not require this level of low latency and high reliability, there are still key use cases that require it. Therefore, this is a challenge for 5G solutions which needs to be addressed.

Another challenge of real-time communication is determinism. One hindrance to performance for real-time communications is the non-deterministic timing behaviour in wireless industrial communication networks, which is inherent in wireless communications [2]. This is due to factors such as variable propagation delays, security, variable processing of forward error correction (FEC) mechanism, and radio access network (RAN) processing. Furthermore, clock synchronization in hybrid networks incorporating 5G is another unsolved challenge, which needs to be addressed [2]. This is confirmed in the survey results, where 56 % of participants agreed with this statement, and only 13 % disagreed. Although precise clock synchronization has been supported in the form of time-sensitive networking (TSN) functionalities since 3GPP release (Rel.) 16 and extended in Rel. 17 [2], the challenge for clock synchronization is its implementation, where there is no current commercial solution.

Furthermore, native support for layer 2 (L2) communication is a functionality that is required for industrial use cases. The lack of inherent support for L2 traffic in current 5G implementations is a significant limitation. This is reflected by the results of the survey, where 60 % of participants agreed to this statement. Often in industrial use cases, communication is already implemented over fieldbus systems utilizing L2 traffic, whereas current 5G implementations use IP as the network layer protocol. Currently, L2 traffic can be transported over the 5G system via tunnelling through layer 3. However, L2 tunnelling increases complexity and decreases the performance with respect to the timing behaviour due to increased overhead, processing time and transmission time of the L2 messages. Specific use cases that have strict timing behaviour requirements also require the full support of L2 and its properties, like priority support, which are currently not supported by L2 tunnelling. standardised functions, such as support for 5G local area network (LAN)-type service and support of Ethernet PDU Session type, introduced in 3GPP TS 23.501 Rel. 16 [3], can address this issue, once they are implemented and commercially available.

In addition, not all applications served by one network require the same performance. The requirements in terms of the data traffic can even be very diverse depending on the applications, with varying cycle times and varying latency [2], making it more difficult for the network solution to meet all requirements at once. Also, different applications might require the network solution to support multiple services, e.g., supporting both URLLC and mMTC, at the same time [2].

Finally, high-density environments could potentially play a negative impact on the performance of a 5G system. However, the survey results suggests that this negative impact is not currently a significant challenge. 57 % of participants either disagreed or strongly disagreed that high-density environments represent a significant challenge for 5G performance. Although 29 % of participants agreed with this statement.

3.1.2 Deployment related challenges

Further challenges come with the deployment of the 5G system. Firstly, coverage planning in a 5G system is a challenge due to the complicated environments where they are to be deployed. Although 94 % of the survey participants stated that detailed coverage planning is needed for the deployment of 5G/6G NPNs, only 31 % stated that it is always needed. 63 % of the participants stated that this is only necessary selectively, i.e., for specific environments, and not in all cases. Example environments given by the participants, where coverage planning is needed, include: for enabling the seamless connectivity between NPN and public networks (PNs), for industrial environments with many metallic surfaces, for positioning applications, and for manufacturing or expansive logistic halls with more than 500 subscribers.

Secondly, the need for expert knowledge as well as the dependence on external service providers are challenges. A large majority of the survey participants, 87 %, agreed that the need for expert knowledge or reliance on external service providers is critical when deploying 5G. A reason for this is because of the complexity of the installation and deployment. To resolve this challenge, the 5G solutions must come with better documentation and improved ease of use.

With regards to whether scalability issues pose a major challenge to 5G NPN deployments, the opinions were diverse. 33 % of participants agreed or strongly agreed with the statement, 27 % answered neutrally, and 40 % disagreed or strongly disagreed. Although it might be a concern for some, it does not appear to be a concern for a majority of the stakeholders.

3.1.3 Security and resilience related challenges

According to [4], while existing regulations such as those from European Agency for Cybersecurity (ENISA) and the Federal Communications Commission (FCC) provide a baseline for 5G security, they do not address the specific requirements of industrial networks. However, from the results of the survey, it does not appear as if security and resilience contribute to the major challenges determined for 5G systems. Most participants of the survey, 93 %, disagreed that the vulnerability of 5G networks to cyberattacks is significant. Therefore, this is not perceived as a significant challenge for deployment of industrial 5G networks.

3.2 Economic challenges

[5] shows, while the capital expenditure (CapEx) of cellular networks takes almost two thirds of the total cost, the relative operating expense (OpEx) is shown to be only one third. This high initial CapEx could explain why 88 % of the survey participants either agreed or strongly agreed that the high cost of 5G significantly slows its adoption. One respondent was neutral (6 %), and another disagreed (6 %). However, [5] shows that the long-term costs (OpEx) of 5G are lower than those of other wireless technologies. These varying perceptions show that there is a need for further case studies and business analysis to gain a clear understanding of the costs of 5G NPN. 5G-ACIA White paper "Business Value

and Return-on-Invest Calculation for Industrial 5G Use Cases." [6] addresses this issue by introducing a method to estimate the business value of 5G NPN for diverse industrial applications.

Another challenge to 5G deployment is industry expectations about its future revenue prospects and the extent to which 6G might influence these prospects. To investigate this, the survey asked if the launch of 6G will limit the monetisation opportunities for 5G. Half of participants expect some negative impact of 6G to the 5G monetisation, while nearly one-third disagree and the remainder are neutral. This shows an uncertainty regarding the economic effect of 6G roll-out on 5G monetisation.

A participant further highlighted how technical and standardisation challenges lead to economic barriers, noting that implementing L2, TSN and URLLC with acceptable low latency for a reliability of 99.999 % requires new hardware. This puts a strain on the financial resources or a viable business case to upgrade existing 5G Release 15 systems to any stakeholder. They noted that while pilots based on later 5G releases exist, these currently offer no affordable joint solution for deploying private networks, e.g., with TSN. The lack of an international Car-to-X standard further complicates the development of base stations optimized for such use cases. As a result, stakeholders face both high upgrade costs and uncertainty about long-term viability, making it difficult to build a solid business case.

3.3 Standardisation challenges

The standardisation of 5G technology is far ahead of its implementation as reported in [7]. For example, some relevant features, such as URLLC, New Radio (NR) Sidelink, and L2 traffic, have been standardised, but as of today there are no information on commercial implementation. According to the survey results, all of the participants 100 % either agreed or strongly agreed with the above-mentioned statement. In another question, it was asked if the participant agrees with the statement "Some standardised features might never be implemented." 64% of participants strongly agreed and 29 % agreed, with one participant being neutral.

This issue can result in delayed product roadmaps. This delay means manufacturers require additional time to design, test, and produce devices, which limits the choices available to early adopters and slows broader market uptake.

3.4 Regulatory challenges

Reliable industrial connectivity requires licensed spectrum, since controlled access ensures performance and stability. Therefore, managing spectrum for industrial use is crucial for adopting wireless solutions. Consequently, in the future, allocated spectrum should be reserved for NPNs to ensure industries have secure and predictable access to 5G for critical operations [8]. According to the survey results, more than 75 % of the participants consider having an allocated spectrum for NPN is an enabler for German industry. The application process of NPN 5G spectrum licenses from the *Bundesnetzagentur* is generally considered to be low in time and effort. 60 % of the participants see also the advantages of having spectrum allocated for NPN outweigh the negatives of having less spectrum available for public MNOs.

The German local spectrum is rather unique. Each country regulates how and which spectrum is allocated to NPNs differently. Although there may be similarities between countries. The differing regulations make it challenging to use this allocated spectrum worldwide, since it is possible that the allocated spectrum is different between countries. This potentially leads to coexistence difficulties at the border of neighboring countries. The differences in regulations could be addressed at an international level to coordinate NPN allocated spectrum and improve coexistence across borders. While MNOs highlight the uniqueness of the German spectrum, some experts believe that this claim is primarily interest-driven.

They argue that production facilities should be able to implement NPNs independently, without being forced to rely on MNOs.

Each 5G system must have a Public Land Mobile Network (PLMN) identifier (ID). International Telecommunication Union (ITU) allocated the Mobile Country Code (MCC) 999 for use in private networks [9]. Since this MCC can be used by NPNs with any Mobile Network Code (MNC), neighboring NPNs can have the same PLMN ID without knowing. This could cause problems between the networks. When asked if obtaining a PLMN ID for their NPN would be beneficial, 50 % of participants agreed that it would be beneficial, while 42 % where neutral and 8 % disagreed. Therefore, national regulators and international organizations should look into the possibility of allocating PLMN IDs for NPN operators on a voluntary basis.

Industrial environments usually rely on certified devices to be able to trust that the devices will work as expected. Currently, no certifications for industrial 5G devices or systems are available to ensure the performance and capabilities of the products. Certification of devices and systems can increase the uptake and trust of 5G solutions in industrial environments. It is essential to focus on internationally recognized certifications, since regional certifications will increase the cost of development and decrease the return on investment.

4 Lessons learned from 5G

There are takeaways and lessons learned derived from the challenges and suggestions of what can be done differently in 6G. These takeaways, like the challenges, are divided into sections on technological, economic, standardisation, and regulatory lessons.

4.1 Technological lessons

With regard to technical lessons when planning, deploying and operating a 5G network that could be derived from the challenges, the survey, and the experiences of deployed networks, there are a number of takeaways that can be noted for: the organizational planning; the technical planning and engineering; the deployment and commissioning; and the operation and diagnostics. There are also relevant technical lessons that revolve around 5G functionality in general.

4.1.1 Organizational planning

One important aspect when planning a 5G network is to prepare a systematic requirements specification, which is a structured documentation of all functional and non-functional requirements. According to the survey results, 81 % of participants agreed that systematic requirements specification is important for ensuring smooth integration of 5G/6G solutions. Planning a realistic schedule for delivery, integration and learning phases is also instrumental for the deployment of the network. Finally, developing a good cross-team communication between information technology (IT) and operational technology (OT) is very important from the start to prevent difficulties in the later phases of planning and deployment. Planning for any integration problems between IT and OT from the start is less costly than solving problems after deployment.

4.1.2 Technical planning and engineering

When planning the technical aspects and engineering of the 5G network and solutions, a few lessons can be taken from previous experiences and the survey. Firstly, there is the importance of leveraging simulations for planning, engineering, and diagnostics before installing the network. According to the survey, 50 % of participants noted that they utilize simulations in network planning. Of the nine options available, the top three utilizations for simulations were: coverage prediction; interference analysis and frequency planning; and cost estimation. Further utilization options include quality of service validation, antenna configuration and beamforming design, pre-deployment feasibility testing of a specific application, post-deployment performance monitoring and optimisation, "What-if" and scenario testing for network changes, and troubleshooting operational issues. The other 50 % of participants noted that they did not use simulations. One of the participants noted that they do not work on network planning, so simulations are not needed. From the given answers to the survey question, network planning is not the sole use of simulations, but can also be used for cost and application planning, as well as monitoring.

Another lesson learned through experience was the forethought needed from the start with regards to the PLMN IDs used by NPNs, so that these networks work with all devices. As noted in Section 3.4 all NPNs can use the MCC 999. But during rollout, many 5G devices were not able to connect with PLMN IDs using this MCC. After feedback from the end users, most 5G devices are now able to utilize these PLMN IDs. It shows that forethought regarding PLMN IDs is essential for ensuring compatibility across devices in 5G/6G, which was confirmed with 46 % agreement by the survey participants. Although not a major point, this should be considered when developing 6G.

Radio propagation in specific and difficult environments is always an important topic for industrial use cases, due to the high density and high amount of metal. It has been shown though that radio propagation with mid-band frequency is possible in very dense shop floors, showing that 5G/6G has a place in industrial environments, making planning easier. This was confirmed by the survey participants, 57 % of which agreed to the statement. Although this does not mean that detailed coverage planning for industrial environments is not needed. This type of environment was one of the selected environments noted for needing coverage planning (see section 3.1.2). Moreover, 5G can adapt the data transmission to the varying channel conditions via the modulation and coding scheme (MCS), which determines the number of useful bits that can be carried by one resource element (RE) [10]. Better channel quality results in the transmission of a higher number of useful bits per RE. Therefore, conducting measurement campaigns before deployment, during commissioning, and throughout operation to determine channel conditions is beneficial, since it enables continuous optimisation of the network's performance.

Finally, the topic of technical planning and engineering can also be looked at from the viewpoint of upgrading existing production lines to 5G. 57 % of survey participants disagreed with the statement that the production lines should be upgraded to 5G by replacing legacy technologies with 5G, rather than adding 5G as an add-on. So more participants believe that 5G as an add-on is a better choice.

4.1.3 Deployment and commissioning

When deploying and commissioning the network and devices, some takeaways were discovered that should be noted. Firstly, there is the integration of the devices in the network. Specifically, there were difficulties in getting specific modes of user equipments (UE) to work with the network, or even getting the device to connect with the network. One example of the latter is with the security settings between different producers of device and network hardware, which initially prevented the device from connected until the correct settings were found. In many occasions, expert knowledge was needed just to allow the device to connect or to set modes of the UE. This is confirmed by participants of the survey, where expert knowledge is deemed as necessary when implementing a 5G system (see section 3.1.2 for more). The ease of use or ease of configuration can and should be improved. But this will depend a lot on the implementation in the UEs and 5G/6G system. More on the improvement of the ease of use for 6G is discussed in Section 5.

As described in the technical planning lessons learned (section 4.1.2), upgrading existing production lines to 5G is seen as most feasible by adding on 5G technology, rather than replacing legacy equipment. A further takeaway is that the upgrade is possible, and that the upgrade from 5G to 6G must be maintained as well. The upgrade of 5G to 6G is described more in depth in Section 6, as well as in another 6G Platform's white paper "German Perspective on 6G – Use Cases, Technical Building Blocks and Requirements" [11].

4.1.4 Operation and diagnostic

Once a 5G network is operational, there is always the possibility that the network does not operate as required or problems occur. For this reason, it is important to run measurement campaigns on the network during commissioning, as well as during operation and for diagnostics after installing the network. This was agreed to by 100 % of the survey participants.

4.1.5 Further 5G functionality

Further technological lessons learned have less to do with the lifecycle of the 5G network, but more to do with the different expected functionality of 5G. This includes specific abilities that devices and networks should share, like interoperability; innovative systems that can be utilized, like Open RAN (ORAN); or innovative functions promised for 5G, such as embedded SIM (eSIM) and improved power consumption. These lessons have to do with what is required for the end user in different industries.

ORAN is an innovative idea developed for the 5G system to increase the interoperability between the cellular network equipment from different vendors. Although some ORAN solutions were initially difficult to work with due to the need for solutions to mature, it is important to allow this maturity into 6G, so that the development can continue seamlessly and be built upon, rather than having to start anew with 6G releases. It was only slightly agreed to by the survey participants, with 33 % agreeing and 53 % responding neutrally to the question, that the continual development of ORAN solutions is essential for 6G development. One downside to utilizing ORAN solutions is that it can add complexity for the IT department of the company. The survey participants were asked which of the offered strategies would most effectively reduce the complexity that ORAN introduces, thereby facilitating smoother implementation. 64 % responded that standardised integration frameworks, such as open application programming interfaces (API) and common data models, would be most effective, 28 % responded with automated orchestration and lifecycle management tools, and 0 % responded with comprehensive training and documentation for IT teams. Consequently, there is still potential for the technology to improve, and this is seen as the best way to improve ease of implementation.

Devices from different vendors can report different channel quality indicators, such as received power and reference rignal received power (RSRP), which cannot be compared with one another. This lack of standardised methods can be an issue when comparing channel quality indicators of devices from different vendors, such as for network orchestration techniques. It will be difficult for the system to compare and interpret measurements across devices. 64 % of participants agreed that different channel quality indicators from various devices makes it challenging to compare and interpret measurements across devices for network management.

There are some further gaps in the 5G functionality, which have not yet been made commonly available in commercial products. In some cases, they are not available at all. One such gap is the support of eSIM support. The support of eSIM would increase the ease of use for industrial use cases, as long as the configuration is simple and straightforward. Another gap is the need for decreased power consumption in UEs. The power consumption is still too high and must be improved for battery powered industrial 5G devices. This could be covered by mMTC and reduced capacity (RedCap) devices, but the mMTC branch of 5G is still missing and RedCap devices are not expected to be available before 2027 [12]. Some necessary integration features, such as Ethernet ports, are required by users to be included in more devices for industrial use cases as well. In the survey, participants were required to answer whether they agree that these features are crucial. The surveyed features were L2 tunnelling, eSIM availability, power consumptions issues, integration features and ORAN development. Based on their responses, it is possible to deduce a ranking of these features by calculating the mean of the answers as described in Section 6. From this, eSIM availability appears to be the most important (mean: 1.31), followed by power consumption (1.25), integration features (1.07) and L2 tunnelling (0.93), where a tendency towards agreement can be observed. ORAN development only scored 0.33 as a mean value, as 8 out of 15 responses were neutral. However, among the non-neutral responses, 5 agreements (3 of them strong) slightly outweigh the 2 disagreements (1 of them strong).

Furthermore, some of the previously mentioned features and other additional features, like quality of service, traffic flow prioritization, and network slicing, are only partially standardised, partially implemented, and often rely on proprietary extensions. Although no survey participant stated that the solutions were mostly proprietary, 37.5 % stated that there is a mixture of partly standardised and partly proprietary solutions, which is causing issues leading to integration challenges. While 50 % stated that it was mostly standardised, meaning it is interoperable with minimal vendor specific tweaks. 12.5 % stated that there is a standard core, but the advanced functions are proprietary.

The gaps discussed in the proceeding sections show the need for extensive investment in further research and development. Research plays an important role in determining feasible solutions. Companies will thus be more willing to commit to developing industrial network solutions, if the path forward is clearer.

4.2 Economic lessons

Referring to the lessons learned described in section 4.1.2 regarding the full-scale migration from legacy technologies to 5G in production lines, when asked whether this migration would be economically justifiable, 71 % of participants either disagreed or strongly disagreed with this statement. This corroborates previous findings that suggest the industry would prefer 5G to be an add-on to existing technologies.

4.3 Standardisation lessons

To address the standardisation challenges described in section 3.3 some suggestions are derived from the survey results of a multi-select question. 75 % of the respondents think that the focus should be only on features with clear implementation roadmaps and industry demand. 69 % think that addressing this mismatch requires tighter coordination between standardisation bodies and implementers. 19 % believe that the standardisation should continue defining advanced features early, even if adoption is uncertain. One respondent suggested that technical specifications should be defined only for features which have clearly proven their economic feasibility and success. And another respondent specified that the need of operators should be taken into account by standardisation bodies.

The next finding of the survey is about how far specific features' implementation is from the standard and, if they might never be implemented, what could be the reason. The possible options were "On pace", "Behind", "Far behind" and "Might never be implemented". Figure 2 shows the number of each option selected for each feature. Features are sorted from the most far behind feature to the most on pace feature from the top to the bottom. The results show that key 5G features are lagging significantly behind their standardisation. The URLLC and NR Sidelink are seen as the slowest to mature. By contrast, Private / Industrial networks stand out as advanced with 44 % saying they are already on pace. Participants were also given the option to write in other features and their current state of implementation. Other features mentioned include URLLC implementation in telecom provider networks (i.e. PNs), which was designated as might never be implemented, and Security & Trust Management (Zero-Trust, secure identities, quantum-safe encryption) which is seen as far behind.

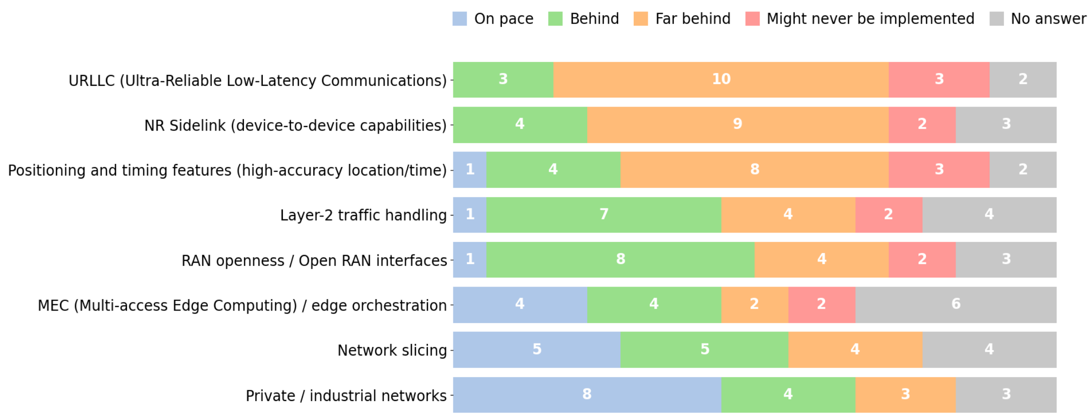

Figure 2: How far behind the implementation is from the standard according to the survey results.

Figure 3 shows the result of the survey regarding why 5G features might not be implemented. It can be seen that the main reasons are insufficient market demand, technical complexity and immaturity, and high cost. The least important reason is the security or privacy concerns across all features. URLLC is seen as lacking market demand, while ORAN is most hindered by interoperability issues. For positioning and timing features the technical complexity is pointed out as the key barrier. Participants also mentioned other features: TSN, which they saw as too technically complex or immature, and AI-native network management, where vendor fragmentation and lack of interoperability were highlighted. What stood out most was that network slicing is seen to be facing the biggest obstacle from regulatory and policy barriers. The potential reason for this is discussed in section 4.4.

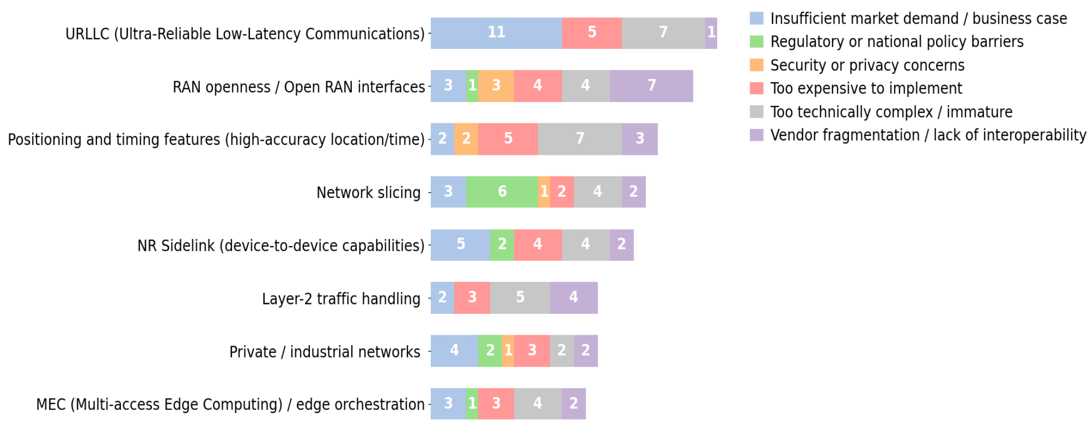

Figure 3: Why 5G features might not be implemented according to the survey results.

4.4 Regulatory lessons

As mentioned in Section 4.3, 33 % of the participants see regulatory and policy barriers as an obstacle for implementation of network slicing. This could be because the core idea of network slicing, treating different types of traffic differently, conflicts with the principle of network neutrality. As highlighted in the German regulator's factsheet on net neutrality [13], differentiated traffic management is only permitted under strict conditions, which could significantly constrain the implementation of network slicing.

5 Innovative solutions for 6G

Understanding the expected timeline and deployment models for 6G is critical to guiding research and design decisions. The survey results show that 50 % of participants expect the first commercial deployment of 6G around 2030, and 44 % expect it between 2030 and 2035. One participant expects it after 2035. This creates a tight window for maturing technologies, aligning standards and implementations before the roll-out. Another survey result revealed no agreement on deployment models for 6G. 56 % of participants either disagreed or strongly disagreed that 6G will primarily be deployed in NPNs, while 25 % agreed, and the rest were neutral. These survey results suggest that 6G deployments are likely to occur within a short timeframe and that the solutions need to be technically flexible and compatible with different deployment models. However, the technical design choices for 6G should not only address the deployment flexibility but also align with the most important market segments. For this reason, the survey explored which market segments are considered most important for 6G monetisation by the participants. The results are shown in Figure 4. As it can be seen, the segment "automotive" ranked highest (most important), followed by "manufacturing" and "personal use", which were rated very close to each other. The segments "logistics" and "healthcare" followed, while "tourism" was consistently ranked least important. Three participants specified XR applications, indoor logistics, and defence as other important segments.

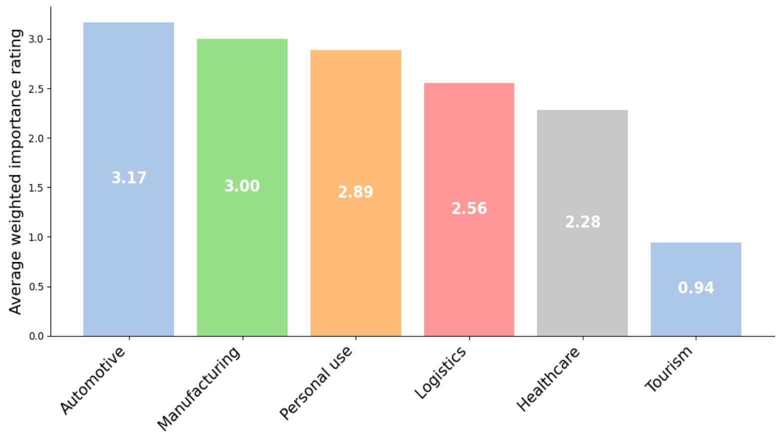

Figure 4: Importance rating of the market segments for 6G monetisation.

As 6G development moves from vision to concrete research and design, it is critical to be aware of the challenges and lessons learned discussed in sections 3 and 4. Experience from 5G has shown that high costs, complex configurations, and operational difficulties can significantly slow the adoption of cellular networks. The following sections summarise the findings of the survey that address these priorities. First, it explores strategies to make 6G more cost-effective. Second, it identifies ways to simplify network operation and management. Third, it emphasises the importance of backward compatibility to ensure a smooth transition from 5G. Finally, it highlights the need for interoperability across vendors and systems to achieve a truly integrated 6G ecosystem.

5.1 Making 6G more affordable

In order to make 6G more affordable for industrial applications, survey participants proposed several strategies in a multi-select question:

- Modularity:

  50 % of participants believe that implementing a modular network architecture would effectively reduce costs. This approach allows for customisation, addressing the high cost associated with network deployment. [11] identifies modular and service-oriented architectures as enablers of the adaptability and scalability of 6G systems.

- Backward compatibility:

  36 % emphasize the importance of ease of migration from legacy technologies. This ability reduces migration costs.

- Adaptability:

  29 % of participants support designing 6G to adapt to evolving use cases, ensuring long-term sustainability by aligning technological advancements with industry needs and consequently reducing the cost of deployment.

Other suggestions from participants included making modems and receivers cheaper than LTE or Wi-Fi, as well as adopting software-defined and machine-learning–driven architectures and components.

Although it was a multi-select question, more than 70 % of participants only selected one option. Due to this high number, it is possible that participants misunderstood the type of question and only selected the most important option in their opinion.

5.2 Simplifying Operation and Configuration

Another suggestion touches on the improved ease of operation and configuration of the cellular systems. A majority of the participants, at 71 %, saw potential to design 6G systems to be easier to operate or configure than current 5G systems. All others, who responded to this question considered the inherent complexity as a limitation allowing only for marginal simplification.

Regarding promising strategies to achieve this simplification, survey participants weighted the following suggested improvements on the technology almost equally by a multi-select question:

- standardised, user-friendly interfaces (e.g., unified dashboards) (60 %),
- Automation and AI-driven configuration tools (reduce manual setup) (60 %),
- Modularising and streamlining the network architecture (70 %),
- Simplifying and standardising protocols (60 %)

Interestingly, improvements on the training, documentation and support were not seen that crucial to increasing simplicity and ease of use of future systems (20 %). This was also confirmed by the question regarding the reduction of ORAN complexity, presented in Section 4.1.5. No one selected the comprehensive training and support as the most effective option, preferring standardised integration frameworks and automated orchestration and lifecycle management tools. In conclusion, there seems to be less a lack of documentation, but rather a potential for improvement on the technology side, its standardisation and the opportunities that AI and automation may provide, which could increase the potential for Plug & Play solutions.

5.3 Ensuring Backward Compatibility and Seamless Integration

Only a few participants, 20 %, believe that 6G will only be used in greenfield scenarios, whereas the majority disagrees, 33 %, or even strongly disagrees, 40 %, to this statement. This result is also consistent with the assessment that 60 % of participants agreed or even strongly agreed that it would be a dealbreaker for 6G, if its radio interface would not be backward compatible. Only 20 % disagreed here. A clear majority, 93 %, approves the feasibility of streamlining the transition from 5G to 6G by adopting a modular hardware / firmware approach, i.e., using replaceable 5G/6G radio modules combined with updatable firmware. However, the establishment of industry-wide standards for modules and firmware interfaces is seen as a crucial condition by most of them, 71 %. The participants also mentioned additional conditions and reasons:

- This would require a strong vendor ecosystem and certification. On the one side, there is a highly competitive situation in RAN and a high complexity, on the other side multiple vendors would need to commit to interoperable modules. Certification programs would ensure compliance and avoid hidden incompatibilities. standardised interfaces are also highly important to avoid vendor lock-ins and incompatible modules. Hence, standardisation bodies (3GPP, ORAN ALLIANCE, ETSI) are crucial here.
- The same spectrum should be operable in parallel 5G and 6G air interfaces, as PNs will need to support LTE and 5G for much longer than 2035. Therefore, a harmonised core is essential. Also, a clear plan to enable 6G in existing and in-use 5G and 4G frequency bands is required. Antenna nodes must be flexible to run all generations from 4G to 6G in the same hardware box.
- Another argument was brought that 5G will be sufficient for the majority of the use cases, whereas 6G might be needed only where specific 6G features or capabilities are required (e.g., URLLC, industrial timing, L2 switching, TSN, prediagnostics of channels/interference), also motivating for the parallel existence of different standards. A potential is seen in software-defined and ML-based components as they allow for easy compliance with the 6G lifecycle for products with a lifetime typically longer than the 3GPP release cycle (automotive, space, aerospace, . . .). In other words, long-term compatibility is required on both sides, the network and the application.

5.4 Interoperability and Vendor Collaboration

Related to that is the seamless interoperability of 5G/6G systems and applications across different vendors, which was seen as a requirement for the off-site development for later on-site integration by 67 % of participants, who answered with agreement or even strong agreement, as opposed to 17 % neutral, 8 % disagreement and 8 % strong disagreements. Without this interoperability, it cannot be ensured that an application will work until it is tested in the target network, adding to the cost of development and commissioning the final product. Again, the importance of open industry-wide standards and rigorous certification along with thorough testing was highlighted.

6 Recommendations and conclusions

This section summarises the key insights derived from the survey and analysis presented in previous chapters. It provides a set of practical recommendations to guide future 6G research, design and deployment efforts. Finally, the section concludes with a summary of the key lessons learned and the open questions that remain for further discussion.

6.1 Actionable Recommendations

- Adopt Modular Network Architecture:

  Implement scalable and customisable solutions to effectively target different market segments. This enables networks to adapt dynamically to changing demands without requiring complete overhauls. This enables purposeful networks where network can be driven by the use case.

- Guarantee Backward Compatibility:

  Ensuring that 6G radio interfaces can coexist with 4G and 5G networks and supporting legacy devices and operators is crucial. This minimizes disruption during the transition period and allows for a gradual migration to the new technology. This could be guaranteed by designing 6G nodes with interchangeable radio modules to support multiple generations of connectivity and with updatable firmware to remain aligned with evolving standards, which would be possible by establishing industry wide standards and firmware interfaces. This would also avoid vendor lock-in.

- Accelerate Native L2 Support:

  Native L2 support should be mandated in 6G as a high priority, while continued support for L2 tunnelling should be guaranteed as a minimum fallback.

- Implement AI-Driven Automation:

  Deploy automated planning, configuration, and orchestration tools that reduce manual setup time and operational complexity.

- Strengthen Interoperability:

  Establish standardised test and certification processes aligned with the IEC 63595, which is currently under development in TC65 SC65C WG16, to verify secure and reliable interoperability. The testing will be described in Part 5: Test Methods of the IEC 63595 series. Additionally, adopt common data models and unified dashboards across vendors to lower integration effort.

- Coordinate Standards and Market Demand:

  Align standardisation bodies with real world implementation roadmaps and prioritise features with proven commercial viability (e.g., URLLC, L2 support, eSIM) before introducing advanced capabilities.

- Investment in Research & Development:

  Continuous investment in R&D is essential for advancing 6G. This can include developing new hardware, software, and network architectures that address the challenges mentioned in this document.

6.2 Conclusions

In conclusion, the transition from 5G to 6G should be guided by the lessons learned from early non-public (private) network deployments. Stakeholders can overcome the cost and technical barriers that slowed down 5G adoption by adopting modular, interoperable, and AI-enabled architectures while ensuring backward compatibility and regulatory alignment. The successful implementation of 6G will enhance telecommunications capabilities and pave the way for future technological advancements. To realise the full potential of 6G, it is essential that all stakeholders involved, MNOs, governments, regulatory agencies, service integrators and vendors, and standardisation bodies align their efforts.

Acknowledgement

The work was carried out as part of the 6G Platform Germany project (6KISK048, 16KISK050), which is funded by the Federal Ministry of Research, Technology and Space (BMFTR).

Abbreviations

NPN	Non-Public Network
3GPP	3rd Generation Partnership Project
5G	5th Generation cellular technology
6G	6th Generation cellular technology
API	Application Programming Interfaces
AI	Artificial Intelligence
CapEx	Capital Expenditure
eSIM	Embedded SIM
ENISA	European Agency for Cybersecurity
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FEC	Forward Error Correction
HARQ	Hybrid Automatic Repeat Request
IT	Information Technology
ITU	International Telecommunication Union
IoT	Internet of Things
L2	Layer 2
LAN	Local Area Network
LTE	Long-Term Evolution
MCC	Mobile Country Code
MNC	Mobile Network Code
MNO	Mobile Network Operator
MCS	Modulation and Coding Scheme
NR	New Radio
ORAN	Open RAN
OpEx	Operational Expense
OT	Operational Technology
PDU	Protocol Data Unit
PLMN	Public Land Mobile Network
PN	Public Nework
PAS	Publicly Available Specification
RAN	Radio Access Network
RedCap	Reduced Capacity
RSRP	Reference Signal Received Power
Rel.	Release
TSN	Time-Sensitive Networking
URLLC	Ultra-Reliable Low Latency Communication
UE	User Equipment

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Appendix

The following repository contains:

- The figures generated by the LimeSurvey of the survey results in PNG format.
- The documents generated by the LimeSurvey of the survey results in PDF format.
- The raw data of the survey results in xls format.

The link to the GitHub repository: https://github.com/ParvaYazdani/WG3_6GPlatform_SurveyResults