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

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Contents

Executive Summary

The working group “Innovation Management” of the 6G Platform Germany aims to accelerate innovation across the German BMFTR-sponsored 6G programme. Therefore, it acts as an interface between 6G researchers and industrial associations, connecting and supporting start-up incubators, and organising the Founder’s Class – a series of lectures and hands-on experiences for aspiring founders. Drawing on this mission, this white paper documents a systematic exploration of the challenges that were encountered in the industrial deployment of the fifth generation of cellular networks (5G), the lessons learned from non-public network (NPN) deployments, and a set of actionable design principles for the sixth generation of cellular networks (6G). Based on an expert survey, literature review, 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. Ultimately, regulatory frameworks must be updated to address spectrum allocation and cross-border compatibility, thereby paving the way for the seamless global rollout of 6G in industrial and professional deployments.

The paper concludes that the main bottlenecks to the adoption of cellular networks are high deployment costs, complex configuration, and the fact that the implementation of important 5G functions remains unavailable. It also proposes a list of innovative solutions to address these issues. Some examples include backward-compatible network architectures, which are proposed to decrease costs. AI-driven configuration tools and user-friendly interfaces are recommended to simplify complex configurations. Open industry-wide standards and thorough testing are suggested to mitigate interoperability issues. Moreover, detailed reasons are provided for the function implementations that are not yet available, allowing these gaps to be addressed as well.

1 Introduction and Motivation

Cellular networks are gaining attention in the adoption of Internet of Things (IoT) devices due to their mobility, scalability, and wide coverage. However, since the introduction of Long-Term Evolution (LTE), several obstacles, ranging from high infrastructure costs to security concerns, have been revealed. These obstacles have hindered the widespread adoption of cellular networks in industry, even during the current rollout of 5G. By examining industry use cases, this white paper identifies valuable lessons regarding the gaps that cause this impediment. As we move forward to 6G, it is crucial to draw on past experience and mitigate potential risks, such as costs and operational challenges. This awareness enables innovative solutions such as customised network architecture and an AI-driven network orchestration.

NPNs utilising 5G technology have been deployed across various test scenarios in industry and for research into industrial applications. However, the commercial use of these industrial 5G use cases remains limited. Private networks are one option for NPN deployment [1]. Knowledge and experience have been collected in many of these NPN deployments. They are instrumental in identifying the challenges that present themselves, both those that have been resolved and those yet to be addressed. Many lessons can be learned from these deployments and must be applied to improve 5G adoption, the 5G technology itself, and future mobile cellular networks, such as 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, the Berlin 6G Conference, and the IEEE 6G Summits, where seminal lectures, riveting panel discussions, and intense dialogues 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 the entire community can benefit from it. The second point is to gain perspectives from different stakeholders on the challenges and lessons learned by conducting a survey. The survey results will help determine which of these challenges and lessons learned are most important to focus on, thereby facilitating the adoption and success of 6G innovations. 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 relevant stakeholders to enhance the development of future cellular technology. The remainder of the white paper is structured as follows: Section 2 provides a detailed description of the survey and discusses its design and analysis. Sections 3 and 4 discuss the challenges of 5G and the lessons learned from them. 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 scales, multiple-choice, and ranking questions, as well as qualitative questions in open-text format 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 Germany. The working group members 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. Considering only 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 utilising 5G technology for use cases and applications.
- **Service Vendor:** Companies that develop, integrate, and sell equipment, devices, and services for utilising 5G technology.

- **Industry Association:** Associations and organisations 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.

2.3 Data Analysis

After completion of the survey, the results were analysed to determine their significance. For most survey questions, participants could choose any of the given answers, including a “no answer” option if they were not confident or simply did not want to answer. The results of the survey questions were calculated without consideration of “no answers”. Consequently, percentages and other calculations take into account only the participants who answered the questions, leading to potentially different total numbers across 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 that all utilised the same Likert scale. The Likert scale was 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 the mean of all answers to the specific question.

2.3.2 Calculation of the Weighted Average in Ranking Questions

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 in that category, followed by an average relative to the total 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 also multiple-choice questions, with several options to select from. These questions are called multi-select questions. It is essential to note that during the analysis of these questions, when calculating percentages, the totals may exceed 100%.

2.4 Ethical Considerations

The survey was designed so that results cannot be mapped to individual participants.

3 Challenges Faced in 5G

During the rollout of 5G solutions and the implementation of 5G use cases, diverse challenges were experienced. Some challenges have been resolved and overcome, while others remain to be faced. Both should be documented so that the same challenges can be avoided in the next generation of mobile technology, and solutions to the ongoing challenges can be identified. This white paper groups the challenges into four main categories: technological, economic, standardisation, and regulatory challenges. These are presented in the following sections. The challenges outlined were initially gathered through correspondence with various stakeholders, as described in the introduction. Most challenges were then included in the survey described in Section 2 to gain an understanding of the current state of the challenges based on the opinions of different stakeholders in the industry. Moreover, the survey results are presented in this section.

3.1 Technological Challenges

The analysis begins by examining the challenges inherent in the technology itself. These can be categorised into challenges related to performance, deployment and implementation, as well as security and resilience.

3.1.1 Performance Related Challenges

Many challenges with 5G solutions stem from the real-time requirements of many industrial use cases. These use cases demand an extremely high reliability [2]. Furthermore, high reliability is often required alongside low transmission time, 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 constraints of all URLLC use cases due to various factors, including hybrid automatic repeat request (HARQ) retransmissions and processing and scheduling delays, which affect deterministic behaviour. 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. Although many industrial use cases do not require this level of low latency and high reliability, there are still key use cases that necessitate it. Therefore, this is a challenge for 5G solutions which needs to be addressed.

Another related 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

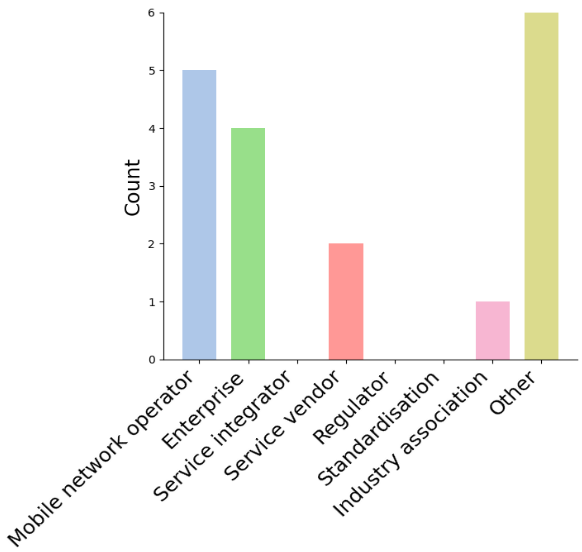

Figure 1: Distribution of participants by category.

inherent in wireless communications [2]. This is due to factors such as variable propagation delays, security concerns, variable processing of the forward error correction (FEC) mechanism, and radio access network (RAN) processing. Furthermore, clock synchronisation in hybrid networks incorporating 5G remains an unsolved challenge that needs to be addressed [2]. This is confirmed by the survey results, which show that 56% of participants agreed with this statement and only 13% disagreed. Although precise clock synchronisation 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 synchronisation lies in its implementation, where there is currently no commercial solution.

Furthermore, native support for Layer 2 (L2) communication is a functionality required for industrial use cases. The lack of inherent support for L2 traffic in current 5G implementations is a significant limitation. This is reflected in the survey results, where 60% of participants agreed with this statement. Often in industrial use cases, communication is already implemented over fieldbus systems utilising 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 degrades timing behaviour due to increased overhead, processing time, and transmission time for L2 messages. Specific use cases with strict timing behaviour requirements also require full support for L2 and its properties, such as priority support, which are currently not supported by L2 tunnelling. Standardised functions, such as support for 5G local area network (LAN)-type services and Ethernet PDU Session type, introduced in 3GPP TS 23.501 Rel. 16 [3], can address this issue once they are implemented and commercially available.

Additionally, not all applications served by a single network require the same level of performance. The requirements for data traffic can be very diverse, depending on the applications, with varying cycle times and latencies [2], making it more challenging for the network solution to meet all requirements simultaneously. Moreover, different applications may require the network solution to support multiple services simultaneously, such as both URLLC and mMTC [2].

Finally, high-density environments could potentially introduce a negative impact on the performance of a 5G system. However, the survey results suggest that this negative impact is currently not a significant challenge. 57% of participants either disagreed or strongly disagreed that high-density environments pose a significant challenge to 5G performance. However, 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 poses a challenge due to the complex environments in which it is to be deployed. Although 94% of survey participants stated that detailed coverage planning is needed for the deployment of 5G/6G NPNs, only 31% said it is always necessary. 63% of the participants stated that this is only necessary selectively, i.e., in specific environments, rather than in all cases. Example scenarios provided by the participants, where coverage planning is necessary, include enabling seamless connectivity between NPNs and public networks (PNs) in industrial environments with numerous metallic surfaces, for positioning applications, and for manufacturing or expansive logistics 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 survey participants (87%) agreed that expert knowledge or reliance on external service providers is critical when deploying 5G. A reason for this is the complexity of the installation and deployment. To resolve this challenge, 5G solutions must be accompanied by better documentation and improved ease of use.

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

3.1.3 Security and Resilience Related Challenges

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

3.2 Economic Challenges

While capital expenditure (CapEx) for cellular networks accounts for almost two-thirds of the total cost, the relative operating expense (OpEx) is shown to be only one-third [5]. 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 indicate a need for further case studies and business analysis to gain a clear understanding of the costs associated with 5G NPN. The 5G-ACIA White paper "Business Value and Return-on-Invest Calculation for Industrial 5G Use Cases". The study in [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 the industry's expectations for future revenue and the extent to which 6G might affect these prospects. To investigate this, the survey asked if the launch of 6G will limit the monetisation opportunities for 5G. Half of the participants expect some negative impact of 6G on the 5G monetisation, while nearly one-third disagree, and the remainder are neutral. This highlights uncertainty regarding the economic impact of 6G roll-out on 5G monetisation.

A participant further highlighted that technical and standardisation challenges create economic barriers, noting that implementing L2, TSN and URLLC with acceptable low latency and 99.999% reliability requires new hardware. This puts a strain on the financial resources and a viable business case to upgrade existing 5G Release 15 systems for 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. These limitations are particularly critical in large-scale, multi-stakeholder application domains such as vehicular communication. The lack of an international Car-to-X standard further complicates the development of base stations optimised 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 is no information on commercial implementation. According to the survey results, all participants (100%) either agreed or strongly agreed with the above-mentioned statement. In another question, it was asked whether 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 delay product roadmaps. This delay means manufacturers need additional time to design, test, and produce devices, limiting the choices available to early adopters and slowing broader market uptake.

3.4 Regulatory Challenges

Reliable industrial connectivity strongly benefits from licensed spectrum, since controlled access ensures performance and stability. Therefore, managing spectrum for industrial use is crucial for the adoption of 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 to be an enabler for the German industry. The application process for NPN 5G spectrum licenses from the *Bundesnetzagentur*[1] is generally considered to be low in terms of time and effort. 60% of the participants also see the advantages of having spectrum allocated for NPN as outweighing 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 (For instance, regulations in Sweden and the Netherlands are similar to the German approach). However, the differing regulations make it challenging to utilise this allocated spectrum worldwide, as the allocated spectrum may vary between countries. This can lead to difficulties in coexistence at the border between neighbouring 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 driven by interest. 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). The 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), neighbouring NPNs can have the same PLMN ID without knowing it. This could cause problems between the networks. When asked whether obtaining a PLMN ID for their NPN would be beneficial, 50% agreed, 42% were neutral, and 8% disagreed. Therefore, national regulators and international organisations should consider allocating PLMN IDs to 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 recognised certifications, as regional certifications will increase development costs and decrease return on investment.

[1]The Bundesnetzagentur (Federal Network Agency) is Germany's national regulatory authority responsible for overseeing and regulating electricity, gas, telecommunications, postal services, and railway markets, with the aim of ensuring competition, network security, and reliable infrastructure provision.

4 Lessons Learned from 5G

This section summarises key takeaways derived from the challenges in the previous section. The takeaways comprise lessons learned from 5G and suggestions for how to do things differently in 6G. As with the challenges, they are divided into technological, economic, standardisation, and regulatory lessons.

4.1 Technological Lessons

Regarding technical lessons that can be derived from planning, deploying, and operating a 5G network, based on the challenges, survey results, and experiences from deployed networks, several key takeaways can be noted. They comprise: organisational planning, technical planning and engineering, deployment and commissioning, and operation and diagnostics. There are also relevant technical lessons related to 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 document that outlines 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 the delivery, integration, and learning phases is also instrumental to the network's deployment. Finally, developing effective cross-team communication between information technology (IT) and operational technology (OT) is crucial from the outset to avoid difficulties in later planning and deployment phases. Planning for integration issues between IT and OT from the start is less costly than solving them after deployment.

4.1.2 Technical Planning and Engineering

When planning the technical and engineering aspects of the 5G network and solutions, several lessons can be drawn 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 reported using simulations in network planning. Of the nine options available, the top three simulation use cases were coverage prediction, interference analysis and frequency planning, and cost estimation. Further utilisation 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 reported not using simulations. One participant noted that they do not work on network planning, so simulations are not needed. From the survey responses, it is clear that network planning is not the sole use of simulations; they can also be used for cost and application planning, as well as for monitoring.

Another lesson learned through experience was the need for forethought from the start regarding the PLMN IDs used by NPNs, so that these networks can work with all devices. As noted in Section 3.4, all NPNs can use the MCC 999. However, during rollout, many 5G devices were unable to connect to PLMNs with this MCC. Following end-user feedback, most 5G devices can now utilise these PLMN IDs. It shows that forethought regarding PLMN IDs is essential to ensuring device compatibility in 5G/6G, as confirmed by 46% of survey participants. Although not a major point, this consideration should be taken into account when developing 6G.

Radio propagation in specific and challenging environments is always a crucial topic for industrial use cases, due to high device density and the presence of large amounts of metal. It has been shown, however, that radio propagation with mid-band frequencies is possible in very dense shop floors, indicating that 5G/6G has a place in industrial environments, making planning easier. This was confirmed by the survey participants, 57% of whom agreed with the statement, although this does not mean that detailed coverage planning for industrial environments is not needed. This type of environment was among the selected environments noted as requiring coverage planning (see Section 3.1.2). Moreover, 5G can adapt data transmission to varying channel conditions via the modulation and coding scheme (MCS), which determines the number of useful bits that can be carried by a resource element (RE) [10]. Better channel quality results in 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 viewed from the perspective 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

During the deployment and commissioning of the network and devices, several key takeaways were identified that should be noted. Firstly, there is the integration of the devices in the network. Specifically, there were difficulties getting specific user equipment (UE) modes to work with the network, or even getting the device to connect to the network. One example of the latter is the security settings between different producers of device and network hardware, which initially prevented the device from connecting until the correct settings were found. On many occasions, expert knowledge was required simply to enable the device to connect or to set the UE modes. This is confirmed by survey participants, who deem expert knowledge necessary when implementing a 5G system (see Section 3.1.2 for more details). The ease of use or of configuration can and should be improved. However, this will depend significantly on the implementation in the UEs and the 5G/6G system. Further discussion on improving the ease of use for 6G is presented in Section 5.

As described in the technical planning lessons learned (Section 4.1.2), upgrading existing production lines to 5G is considered the most feasible approach by adding 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 that problems occur. For this reason, it is essential to conduct measurement campaigns on the network during both commissioning and operation, as well as for diagnostics after the network has been installed. This was agreed to by 100% of the survey participants.

4.1.5 Further 5G Functionality

Further technological lessons learned are less related to the lifecycle of the 5G network and more to the different expected functionality of 5G. This includes specific abilities that devices and networks should share, such as interoperability; innovative systems that can be utilised, such as Open RAN (ORAN); and innovative functions promised for 5G, such as embedded SIM (eSIM) and improved power consumption. These lessons address the requirements for end users across various industries.

ORAN is an innovative concept developed for the 5G system to enhance interoperability between cellular network equipment from different vendors. Although some ORAN solutions were initially challenging to work with due to their need for maturity, it is essential to incorporate this maturity into 6G, allowing development to continue seamlessly and be built upon, rather than having to start anew with 6G releases. Only 33% of survey participants agreed, and 53% responded neutrally, that the continual development of ORAN solutions is essential for 6G development. One downside to utilising ORAN solutions is that it can add complexity for the company's IT department. 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 (APIs) and common data models, would be most effective; 28% responded that automated orchestration and lifecycle management tools would be most effective; and no participant selected 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 signal received power (RSRP), which cannot be compared. This lack of standardised methods can be an issue when comparing channel quality indicators across 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 make it challenging to compare and interpret measurements across devices for network management.

There are some further gaps in 5G functionality that have not yet been widely available in commercial products. In some cases, they are not available at all. One such gap is the lack of support for eSIM. The eSIM support would increase the ease of use for industrial use cases, provided the configuration is simple and straightforward. Another gap is the need for decreased power consumption in UEs. Power consumption is still too high and must be reduced 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, including those less related to 5G/6G, such as Ethernet ports, are also required by users to be included in more devices for industrial use cases. In the survey, participants were asked to indicate whether they agreed that these features are crucial. The surveyed features were L2 tunnelling, eSIM availability, power consumption 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 2.3.2. 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 on average, as 8 out of 15 responses were neutral. However, among the non-neutral responses, 5 agreements (3 of which are strong) slightly outweigh the 2 disagreements (1 of which is strong).

Furthermore, some of the previously mentioned features and other additional features, such as quality of service, traffic flow prioritisation, and network slicing, are only partially standardised and 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 integration challenges. Meanwhile, 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 preceding 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. 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 respondents think the focus should be only on features with clear implementation roadmaps and strong 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. Moreover, another respondent stated that standardisation bodies should take the needs of operators into account.

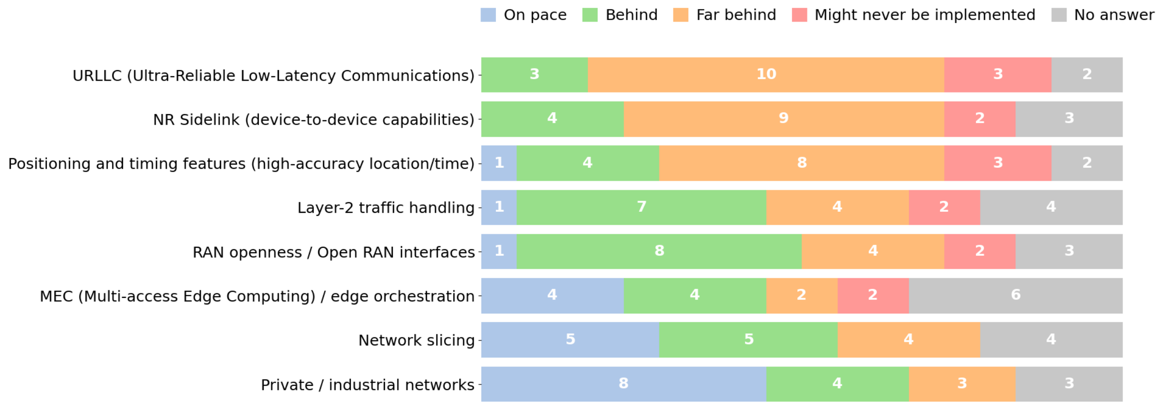

Figure 2: Implementation status compared to the standard, according to the survey results.

The next finding of the survey concerns the extent to which specific features are implemented in accordance with the standard and, if they are not, what the reason might be. 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 farthest behind feature to the most on pace feature from top to 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 and 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 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, as well as high costs. 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, technical complexity is pointed out as the key barrier. Participants also mentioned other features, including TSN, which they perceived as too technically complex or immature, and AI-native network management, where vendor fragmentation and interoperability issues were highlighted. What stood out most was that network slicing is seen as facing the biggest obstacle in the form of regulatory and policy barriers. The potential reason for this is discussed in the next section.

4.4 Regulatory Lessons

As mentioned in Section 4.3, 33% of the participants view regulatory and policy barriers as obstacles to the implementation of network slicing. One reason could be that 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 6G timeline and deployment models is critical for 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 even 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 6G deployment models. 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 solutions must be technically flexible and compatible with various 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 participants consider most important for 6G monetisation. The results are shown in Figure 4. As 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

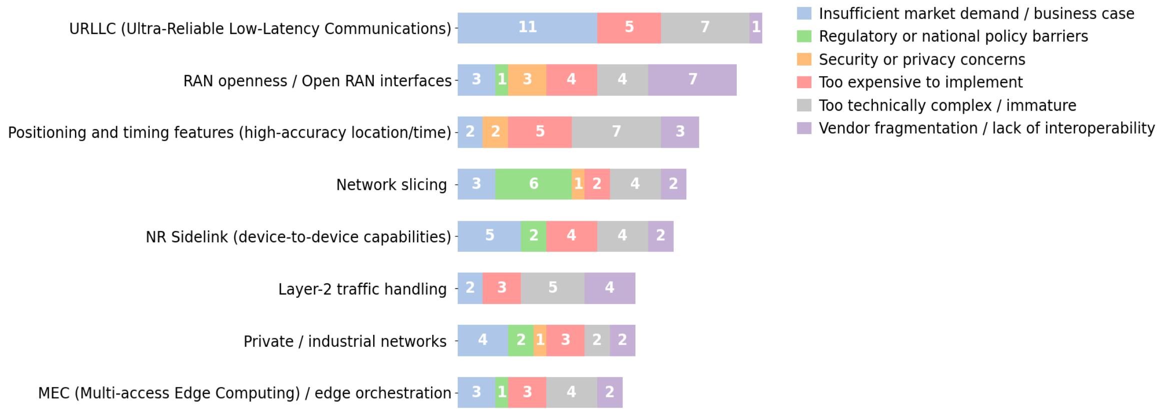

Figure 3: Why 5G features might not be implemented according to the survey results.

consistently ranked least important. Three participants specified XR applications, indoor logistics, and defence as other important segments.

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 survey findings 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. Ultimately, it underscores the necessity for interoperability across vendors and systems to establish a genuinely 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, helping address the high cost of network deployment. [11] identifies modular and service-oriented architectures as enablers of the adaptability and scalability of 6G systems.

- **Backward compatibility**:

  36% emphasise 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 deployment costs.

Further suggestions from participants included making modems and receivers more affordable 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 selected only one option. Given this high number, it is possible that participants misunderstood the question type and selected only the most important option in their opinion.

5.2 Simplifying Operation and Configuration

Another suggestion focuses on the enhanced ease of operation and configuration of cellular systems. A majority of participants (71%) saw potential in designing 6G systems that are easier to operate or configure than current 5G systems. All others who responded to this question considered the inherent complexity 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%),

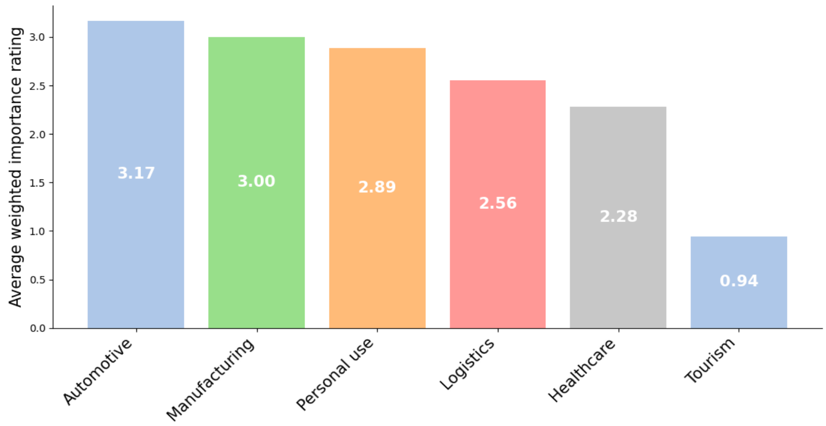

Figure 4: Importance rating of the market segments for 6G monetisation.

- Modularising and streamlining the network architecture (70%),
- Simplifying and standardising protocols (60%).

Interestingly, improvements in training, documentation, and support were not considered crucial to increasing the 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 of 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 be used only in greenfield scenarios, whereas the majority disagree (33%) or even strongly disagree (40%) with 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 were not 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 hand, there is a highly competitive situation in RAN and high complexity; on the other hand, 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 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 the backward compatibility 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, standardisation, 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

Based on the collected insights, the following recommendations can be formulated.

1. **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 which can be driven by the use case.

2. **Guaranteed Backward Compatibility:**

   Ensuring that 6G radio interfaces can coexist with 4G and 5G networks and supporting legacy devices and operators is crucial, as it minimises 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. It would also avoid vendor lock-in.

3. **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.

4. **Implement AI-Driven Automation:**

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

5. **Strengthen Interoperability:**

   Establish standardised test and certification processes aligned with IEC 63595, 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.

6. **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.

7. **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 involved stakeholders, i.e., MNOs, governments, regulatory agencies, service integrators and vendors, and standardisation bodies, align their efforts.

Abbreviations

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

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Survey Data

The white paper is accompanied by the survey data published in the following GitHub repository:

https://github.com/ParvaYazdani/WG3_6GPlatform_SurveyResults

The 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.

(Github Repository)

About 6G Platform Germany

The 6G Platform Germany is a BMFTR-funded project that aims to strengthen Germany's and Europe's technological sovereignty by actively shaping the scientific and strategic foundations of future 6G communication systems. Building on the central role of communication networks in the digital economy and society, the platform contributes to the development of 6G content while providing scientific and organisational support for the implementation of the German-European 6G program. A key mission of the 6G Platform is to connect, coordinate, and mediate between individual projects of the German 6G Initiative, fostering exchange across research, industry, policy, and society. It promotes the harmonisation of national positions with international regulation and standardisation activities and ensures the inclusive consideration of diverse stakeholders, including actors beyond the core mobile communications community. Through targeted science communication and dialogue formats, the platform addresses high-societal-relevance issues and enables early and broad participation in the innovation potential of 6G, thereby supporting the development of a coherent 6G ecosystem and contributing to long-term technological sovereignty.