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OPEN INTERFACES AND INNOVATION IN TELECOMMUNICATIONS

REPORT

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ABOUT CERRE

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EXECUTIVE SUMMARY

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Open interfaces can stimulate innovative entry into the supply of hardware and software components, which can, in turn, lead to more competitive and more resilient supply chains and lower costs. Traditionally, the telecommunications sector has often adopted closed or proprietary interfaces, which has meant that operators have relied on a small number of large suppliers to integrate components into the end-to-end systems which they purchase. Today, however, a potentially revolutionary new network architecture for mobile networks, referred to as Open RAN ("Open Radio Access Network"), will introduce open interfaces in the radio access network, with potentially significant consequences for both the operators who purchase equipment and for those who supply it.

The Open RAN concept is already well advanced and still evolving. It incorporates a set of wide-ranging and fundamental changes to how mobile networks may be supplied, configured, and operated in the future. Some aspects of Open RAN, such as network virtualisation and cloudification, have been under development for years and have their origins outside of the Open RAN environment. These developments will be incorporated into 5G whether Open RAN is adopted or not. This study focuses on a critical aspect of the Open RAN concept, which is the opening of the interface between the Radio Unit ("RU") and the Control Unit ("CU") in the RAN, resulting in an 'open fronthaul', and upon the economic consequences which might follow from this for both operators and suppliers.

We first describe the context for the developments that have led to the O-RAN Alliance initiative which was responsible for developing a standard for the open interface in the RAN (eCPRI 7-2x) and promoting the development of testing and other activities that will be necessary if it is to be commercialised. This section includes a brief history of the development of mobile networks and how the O-RAN Alliance relates to other developments in 5G, including the plans and timelines for implementation. We explain that the Open RAN concept aims to address several different objectives, including contributing to greater competition, resilience, and innovation in the supply chain for equipment and software, and that the open fronthaul concept is an important part of this ambition. We discuss and assess the steps the industry and others are taking to pursue them. We conclude that significant progress has already been made to develop Open RAN and to introduce new suppliers into the RAN supply chain but that all firms will need consistency and clarity from policy makers if they are to make the investments required to enable large-scale commercialisation and that there remain risks that individual firms may seek to disrupt or delay developments, or exploit them unfairly for their advantage. This means that European policy makers should allow new markets to form and firms to pursue their commercial interests but should also be prepared to intervene quickly to resolve disputes between participants if and when they arise. Speed is essential because we think the next 24-36 months will be critical to ensuring the successful development of Open RAN.

We then provide a more detailed economic assessment of how the Open RAN concept might contribute to these objectives. An 'open market' organisation in which different suppliers provide components that customers can then mix and match has both benefits and some risks. The primary benefit is that operators can select each network component from the most cost-efficient or high-quality supplier, resulting in a lower total cost and/or a more optimised system. However, the concentrated nature of the existing supply chain for RAN equipment means that this will only be achieved if developments in Open RAN attract new participants in the supply chain, including the expansion of existing suppliers into new activities and entry by firms from other industries like IT equipment or software development. This is a critical requirement if the O-RAN Alliance is to achieve its objectives.

There are also some potential costs or risks associated with an open supply chain. First, independent vendors may imperfectly take into account the complementarities between their components when designing them, resulting in efficiency losses for the complete system. We, therefore, support the actions taken by the O-RAN Alliance, industry bodies like Telecommunications Infrastructure Project ("TIP"), Governments and individual operators to support and enable collaboration and coordination between independent suppliers at the Research and Development ("R&D") stage in new testing environments and later in the integration and acceptance testing of products before their deployment.

Second, with Open RAN, system integration is likely to migrate from the traditional equipment supplier to another entity. This may be the mobile operators themselves or an intermediary. Large Mobile Network Operators ("MNOs") may derive advantages from having the scale to integrate components themselves. On the other hand, cloudification and other aspects of 5G may reduce scale disadvantages for smaller operators by converting what was previously capital expenditures (fixed costs) into operational expenditures (variable costs). The overall impact of Open RAN and 5G on competition in the downstream mobile market is thus uncertain at this stage. Regardless, it appears that smaller operators have been less involved in the activities of the O-RAN Alliance to date, which is equally the case for 3GPP. Therefore, we recommend policy makers monitor the potential impact of Open RAN for competition between operators as the new technology is deployed on a commercial basis.

Finally, an open market model may stimulate innovation not only in the provision of products and services, but also in the business models employed by the firms that utilise these new technologies. Under the traditional *pipeline* business model, the traditional mobile operator would remain an integrated seller of communications solutions after purchasing and deploying equipment from different suppliers and creating services to meet the needs of different groups of users. With the *platform* business model, a new entity could become more of a platform where suppliers of components and possibly service providers are brought together using open APIs and then interact with users over the platform. If the platform operator also provides its services so that it operates both a pipeline and a platform model simultaneously, in the same way that digital platform providers do, then concerns about self-preferencing and the use of data may arise. Policy makers should ensure that market conditions allow innovative business models to develop as appropriate, whilst being mindful of the issues that may arise if they do.

In summary, the immediate concern for European policy makers should be to ensure that the current activities on Open RAN undertaken by public and private bodies successfully translate into the development of a competitive and diverse Open RAN supply chain and that their products are then integrated into the deployment of virtualised RANs which operators will undertake within the next few years. To achieve this, policy makers should ensure an environment for Open RAN which avoids unpredictable or disruptive interventions, allowing firms, both suppliers and operators, to commit to making investments in the new technologies and new markets to form. Policy makers should support entry by and competition from new suppliers of Open RAN equipment irrespective of their country of origin and they should allow operators the freedom to mix and match components in their networks to best meet their commercial needs.

In the longer term, policy makers should aim to ensure that the deployment of Open RAN does not have unintended consequences for competition in the downstream mobile market and that fundamentally new business models, including using networks as platforms, have an opportunity to develop in a way which further contributes to realising the full benefits of 5G.

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INTRODUCTION

1. INTRODUCTION

In recent years a new network architecture for mobile networks, referred to as Open RAN ("Open Radio Access Network"), proposes to revolutionise the radio access network, allowing operators to mix and match interoperable RAN components from different vendors for the first time. In doing so, Open RAN aims to reduce network costs for mobile operators, facilitate innovation for new products and services and increase competition and resilience in the supply chain. The Open RAN initiative comes at a time when the industry is also engaged in other fundamental changes to other parts of the network architecture, including the core network. Many of these changes will be incorporated into 5G, which is likely to be the first generation of technology to fully reflect many of these developments.

The development of Open RAN has been supported by the O-RAN Alliance, which aims to enhance and accelerate its development by, amongst other things, standardising and opening up the interface between the Radio Unit, which typically is mounted on top of a tower, and the Distributed Unit ("DU"). This interface is typically referred to as the "fronthaul interface" and is often implemented via a (e)CPRI interface.[1] By opening the fronthaul interface,[2] the O-RAN Alliance is seeking to enable and promote entry by a range of new providers of radio equipment, of processing hardware and software, and of tools for the optimisation of the RAN. These products and services were traditionally bundled together by the end-to-end suppliers of network equipment such as Ericsson, Nokia, and Huawei. If successful, the O-RAN Alliance could fundamentally change both the networks that are used by mobile operators and others in the future and the nature of the suppliers and supply chains serving them.

The Open RAN initiative is also linked to recent concerns regarding the security risks associated with mobile network equipment sourced from China, which has led to the exclusion of Chinese vendors like Huawei and ZTE from providing either all or certain parts of the mobile networks in some countries in Europe (and elsewhere in the world), including the RAN. All equipment suppliers currently supply non-interoperable end-to-end RAN infrastructure to mobile operators, with an associated risk of lock-in, as single components cannot be readily replaced by a competitor's products due to proprietary interfaces between RAN elements. Removing equipment supplied by Chinese vendors is therefore costly and difficult, and European operators have been left with only limited options in terms of alternative suppliers.

The Open RAN initiative aims to avoid this by creating a more open network architecture in which mobile operators can mix and match individual RAN components from different vendors, giving them many more options for cost, choice of functionality, and quality in the future.

1 eCPRI: evolved also Ethernet-based Common Protocol for Radio Interface. See the glossary at the end of the document.

2 Open RAN also promotes the openness of other interfaces enabling functionality such as orchestration/management (SMO) of RAN cloud infrastructure (O-Cloud) and modular functionality via pluggable software logic (near-RT/non-RT RAN Intelligent Controllers, xApps and rApps). This report mostly focuses on the fronthaul interface.

Structure of the report

Since not all policymakers and regulators involved will be experts in the field, Chapter 3 provides the context for the developments that have led to the O-RAN Alliance initiative. This includes a brief history of the development of mobile networks, a discussion of the traditional 5G architecture, and how this relates to the Open RAN architecture proposed by the O-RAN Alliance. We explain the importance of the open fronthaul interface in lowering the barriers to entry for suppliers to the mobile operators and thereby promoting competition and innovation.

In Chapter 4, we present a more detailed assessment of the potential economic impact of the open interface concept. We consider its potential impact on the upstream supplier market and downstream mobile operator market, in terms of the degree of competition, investment incentives, and innovation. We also discuss the potential new business models that could emerge alongside Open RAN.

In Chapter 5, we present our conclusions and our policy recommendations.

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MOBILE NETWORK DEVELOPMENTS

2. MOBILE NETWORK DEVELOPMENTS

At the beginning of the 1980s, the first generation of cellular mobile communications evolved along national lines, with each large country having its standards, typically one MNO per country and a single preferred equipment provider. The exception was the Nordic countries that adopted a common standard (NMT450), arranged the mutual recognition of mobile phones, and provided for roaming across the participating countries.[3]

Unlike the first generation of communications, the second generation involved the development and adoption of a common and open Pan-European standard and the coordinated launch of 2G-GSM in 1990. The GSM standard, developed by the European standards organization, ETSI, specified an open interface between the core network ("CN") and RAN, known as the A-interface or 'backhaul' interface. The common standards enabled the development of a competitive equipment supply market for the first time and the open interface meant that the CN and the RAN could now be procured from different vendors. During this period, the number of RAN base station vendors (which included all the CN vendors and Bosch, PKE, TeKaDe, TRT, Matra, and Sat) was approximately double that of the number of CN vendors (which included Ericsson, Nokia, Siemens, Plessey, and Alcatel). The air interface was also standardised, allowing customers a choice of user devices from multiple vendors, all of which would interwork with the RAN and CN of any suppliers.

The third generation 3G-UMTS standard, developed by the global standards body 3GPP, retained an open interface between the CN and RAN and, together with further subsequent iterations of the 3G standard, would open the way for general availability of mobile broadband. However, the collapse of the stock market internet bubble in the late 1990s delayed the introduction of 3G and led to consolidation in the equipment supply side of the market. Nortel went bankrupt, Nokia and Siemens Networks joined forces, as did Alcatel and Lucent Technologies before being taken over by Nokia. Philips exited the market. At the end of this period, two major equipment vendors remained in Europe: Ericsson and Nokia.[4] New Chinese vendors, Huawei and ZTE, entered the European market in around 2004, initially supplying new entrant 3G operators on very competitive terms and later supplying incumbent operators as well.

The development of 4G began with an investigation by the 3GPP standards body in 2004[5] and it was launched commercially in 2010. Again, 4G retained the same open interface between the CN and RAN, although a non-standardised open interface (i.e., not allowing interoperability between vendors), known as the Common Public Radio Interface ("CPRI"), was also introduced between the Radio Unit and the Base Band Unit ("BBU").[6] The absence of a standard interface meant that suppliers retained their proprietary interfaces and RANs continued to be supplied as end-to-end systems. During this

[3] The NMT450 standard was also adopted by the Netherlands, Belgium, and Luxembourg. For an account of the early days of NMT450 see (Meurling and Jeans, 1985).
[4] Note that to assure compatibility with 2G, three regional 3G standards emerged to cover the globe.
[5] For information on the development of 4G, see for instance: Cox (2014); and Rysavy Research (2015).
[6] CPRI is a cooperation between Ericsson, Huawei, NEC and Nokia. See http://www.cpri.info/faq.html

period, the Chinese vendors became significant suppliers of both 4G CN and RAN equipment to operators in Europe.

The developments leading up to 4G are shown in Figure 1 below, with the green links representing open, standardised interfaces and the red links showing proprietary interfaces.

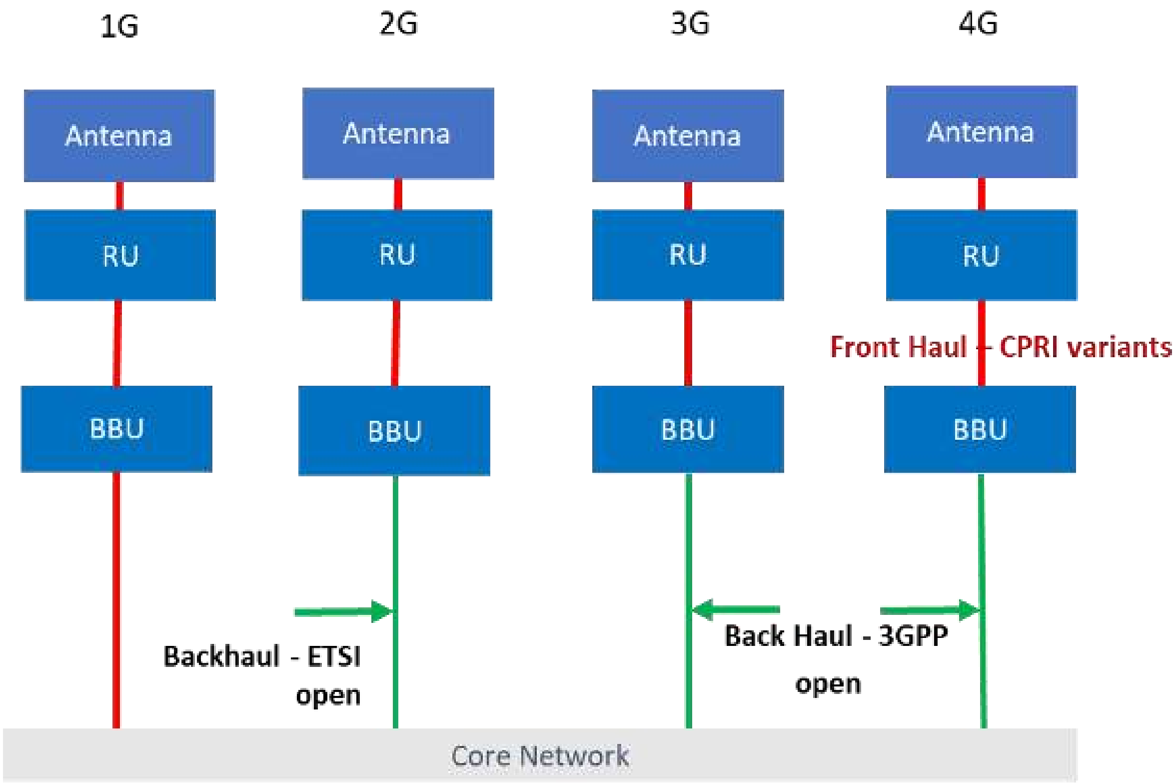

Figure 1. Evolution of interfaces across mobile network generations

In 2011, the activities that would lead to the specification of 5G started with the MicroElectronics Training, Industry and Skills project in the European Union research program FP7 and with working Party 5D in the International Telecommunications Union ("ITU").[7] The specification of 5G started within the global standards body, 3GPP, in 2015. In addition to the regional standardisation bodies, such as ETSI for Europe, various industry groups are contributing to the 5G standardisation work in 3GPP, including the Open Network Foundation, OpenStack, Open Daylight, and OPNFV.

The architecture of 5G builds upon several other features which had been under development for many years. These include Software Defined Networking ("SDN") and Network Function Virtualisation ("NFV"), open Application Programming Interfaces ("APIs"), Artificial Intelligence ("AI") / Machine Learning and cloud-native architectures. These are important features of 5G and are discussed more fully in the Annex, but they are not the primary focus of this study. 5G further extends the RAN

7 Sources: Rysavy Research (2015); Osseiran, Monserrat et al. (2016).

virtualisation efforts that started as part of 4G and allows for network slicing and the differentiation in Quality of Service ("QoS") to meet the needs of a diverse set of 5G use cases.

Current 3GPP Releases of 5G already support the virtualisation of the CN and work is already in progress to complete the virtualisation of the RAN. This includes splitting the BBU into a Control Unit and a remote Distributed Unit, with a new open 'midhaul' interface between the two. This approach is commonly referred to as "disaggregated RAN". This allows more of the software or processing functions to be centralized or 'virtualised' in the CU rather than being undertaken by hardware which is distributed across the RAN. This enables new services to be configured more flexibly and quickly in the RAN without replacing hardware components, and it has other cost advantages too.

The choice of interface specification involves defining interfaces that allow for balancing the amount of centralised DU processing as compared to decentralized RU processing, since this balance has implications for costs and performance.[8] The processing needs of the RAN are more demanding for 5G because of, among other reasons, the use of more advanced antenna technologies such as Massive MIMO, and higher data rates, which lead to heavy signal processing and the need for very low latency communication between RAN components. To respond to this, most of the processing for the 5G RAN will be located at the edge of the RAN (so-called mobile edge computing - MEC) and will make use of hardware acceleration components such as GPUs, FPGAs and purpose-designed chips. The processing needs of low latency applications can also be co-located at the mobile edge, as part of a distributed public cloud, or integrated with the mobile cloud. This means that much of baseband-related processing is done at the RU, which reduces the amount of data that needs to be transported to the DU through the fronthaul interface.

There is a variety of deployment models for disaggregated RAN. These choices are reflected in the options for the specification of the fronthaul interface between the DU and the RU. This will involve an eCPRI interface, which is a more advanced version of the CRPI interface adopted for 4G, but never standardised. The bandwidth required by eCPRI to perform the processing functions across the interface is estimated to be approximately 20% of plain CPRI.[9]

When considering the eCPRI interface, eight different options for the division of processing functions have been identified, but no decision had been made by 3GPP as to which to adopt at this stage. These are shown in Figure 2.

8 For a discussion of the pros and cons of the various splits see Ericsson (2016).
9 Source: "5G at the Edge", 5G Americas (2019b).

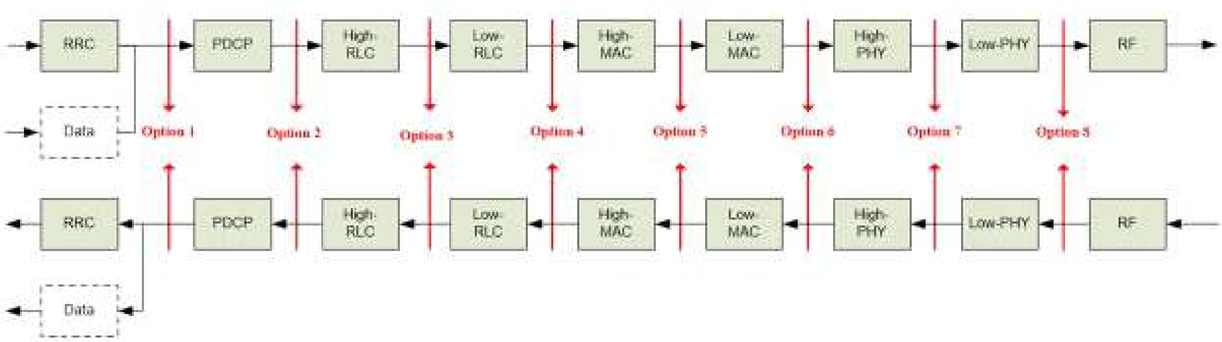

Figure 2. Overview of split options. Source: 3GPP 38.801 in NGMN (2021)

In the long term, more than one of these options will likely be adopted as the optimum trade-offs for processing requirements may differ between, for example, macro cell 5G deployments and small cell 5G.

Whilst 3GPP has yet to adopt any of these options as a standard for the eCPRI interface, to accelerate the evolution towards an open and virtualized RAN and avoid vendors using non-compatible or proprietary eCPRI interfaces, the O-RAN Alliance members have adopted the eCPRI 7-2x interface as their preferred fronthaul interface between the DU and the RU.[10] The difference between the existing virtualised RAN architecture, with a proprietary eCPRI interface, and the O-RAN Alliance concept is shown in Figure 3.

10 Note that splits 6 and 8 are considered for 'further study'. (O-RAN Alliance, 2020).

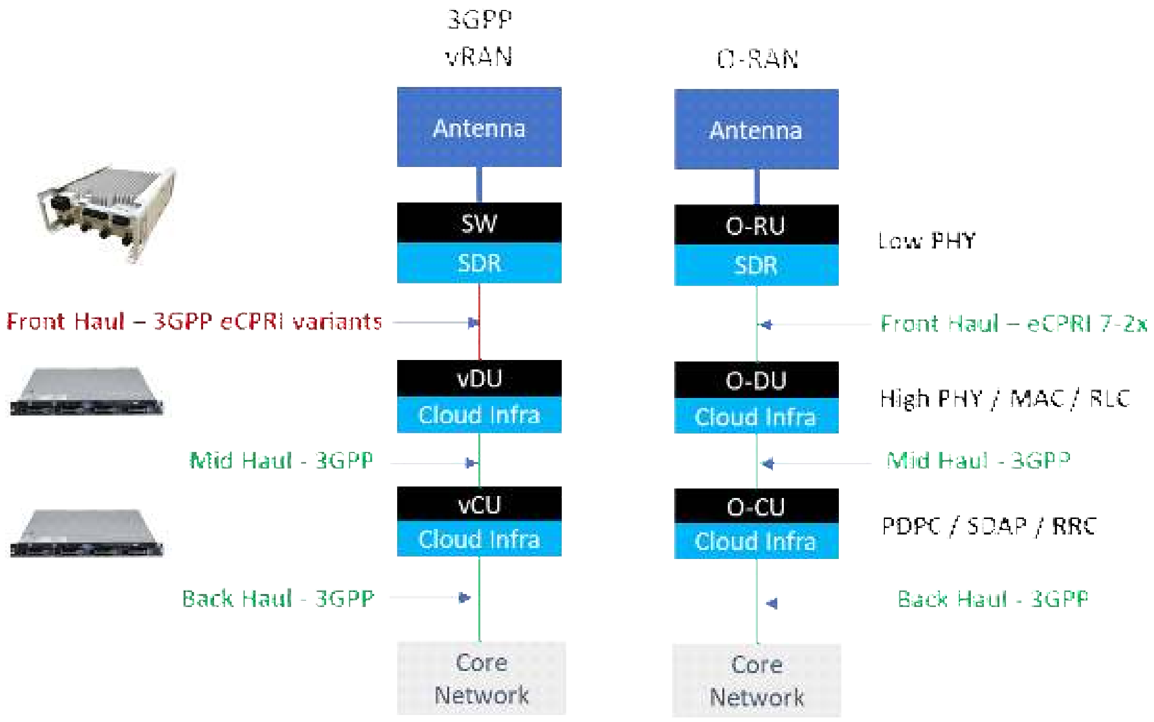

Figure 3. 5G RAN evolution. Source: Adapted from Nokia (2021) and O-RAN Alliance (2018)

In May 2021 it was reported that the O-RAN Alliance had signed a co-operation agreement with ETSI to promote Open RAN and the first O-RAN Specification has been submitted to ETSI as a Publicly Available Specification ("PAS").[11] This represents the first step towards the adoption of the specification, including the eCPRI 7-2x fronthaul interface standard, by ETSI and subsequently by 3GPP.

5G release plan

As with previous generations of mobile technology, 5G will be standardised and released over an extended period. The first deployments already started with Release 15, finalised in June 2018, adding the 5G new radio ("5G NR") operating in new bands, such as the 3.5 GHz, but managed by the existing 4G core (5G NSA or 'non stand-alone').[12] This is now followed by the roll-out of 5G SA as a stand-alone system, with the new radio and a completely new 5G core.

Figure 4 shows the 5G release timeline as anticipated in 2019 (at the top) and the recent update by 3GPP (on the bottom).[13]

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[11] ETSI Work Programme: Details of 'DTS/MSG-001140' Work Item, available here.

[12] Adding a new radio that operates in a band designated for 5G to an existing 4G core network is more an enhancement of 4G-LTE than the first phase of introduction of 5G with new features in support of vertical industries, the so-called stand-alone version of 5G (SA).

[13] For a description of the features in each release, see "3GPP releases 16 & 17 & beyond" a 5G Americas White Paper. (5G Americas, 2021). For an overview of the releases, see the 3GPP website: https://www.3gpp.org/news-events/2145-rel-17_newtimeline.

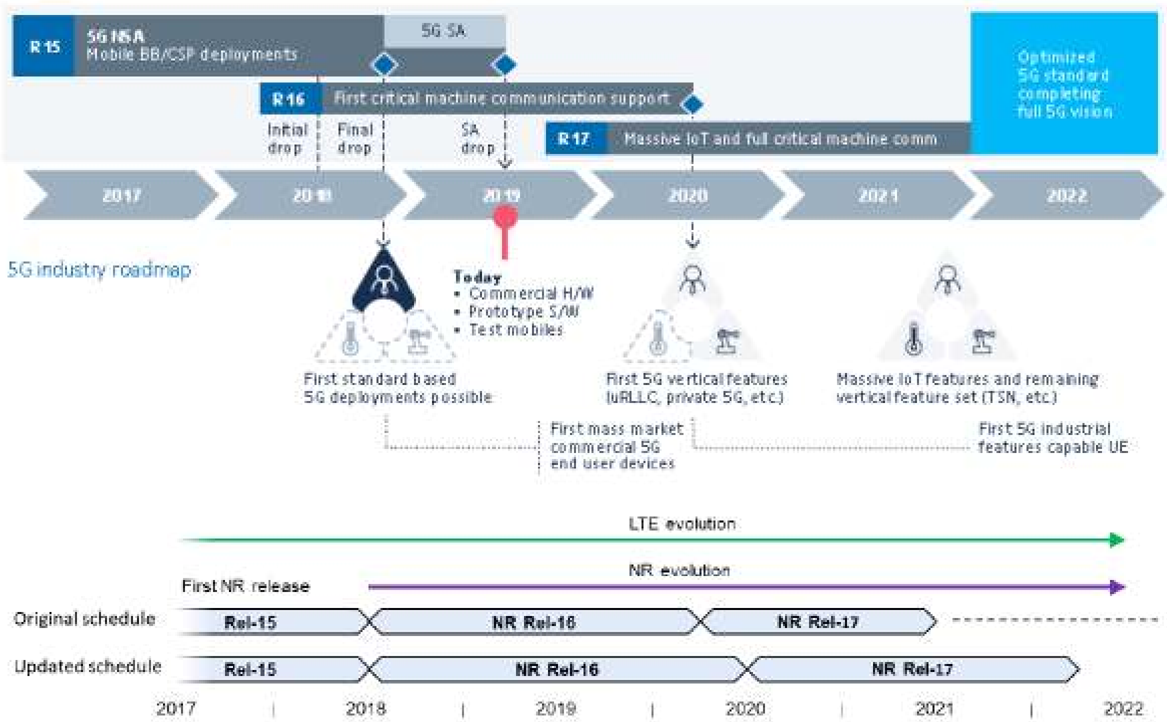

Figure 4. 5G release schedule. Sources: Nokia (2019) and 5G Americas (2021)

2.1 The O-RAN Alliance and other organisations promoting Open RAN

The roots of the O-RAN Alliance activities can be traced back to the RAN virtualisation initiatives of the "Cloud RAN" Alliance led by China Mobile, and the "xRAN Forum", led by AT&T, that was absorbed into the O-RAN Alliance in 2018. See also Figure 5.

The O-RAN Alliance was initiated by the major mobile operators AT&T, China Mobile, Deutsche Telekom, NTT DoCoMo, and Orange in 2018.[14] The stated mission is: "…to re-shape the RAN industry towards more intelligent, open, virtualised and fully interoperable mobile networks".[15] The aim is that "…the new O-RAN standards will enable a more competitive and vibrant RAN supplier ecosystem with faster innovation to improve user experience" and "…will at the same time improve the efficiency of RAN deployments as well as operations by the mobile operators".[16]

In contrast to the membership of standards bodies such as ETSI or 3GPP, the O-RAN Alliance members are all network operators. Equipment vendors fall in the category of 'contributors' to the O-RAN

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[14] Source: https://www.o-ran.org/about.
[15] Ibid.
[16] Ibid.

Alliance. Contributors can contribute to Working Groups, shape and vote on proposals. Contributors leading Working Groups also participate in the Technical Steering Committee ("TSC"). As of September 2021, thirteen vendors are part of O-RAN Alliance's TSC. It is not unusual for firms with common interests to work together to influence standards and other bodies in which finding consensus amongst larger groups of participants can often be difficult, time-consuming, or where firms whose interests may be threatened by proposed changes, may dominate. Today, the O-RAN Alliance website shows the logos of 221 'contributors and academic contributors', next to those of 28 operators, suggesting there is now a strong and broad interest in the topic of Open RAN.[17] This includes support from the traditional equipment suppliers who might be expected to approach the concept of Open RAN with some degree of ambivalence.

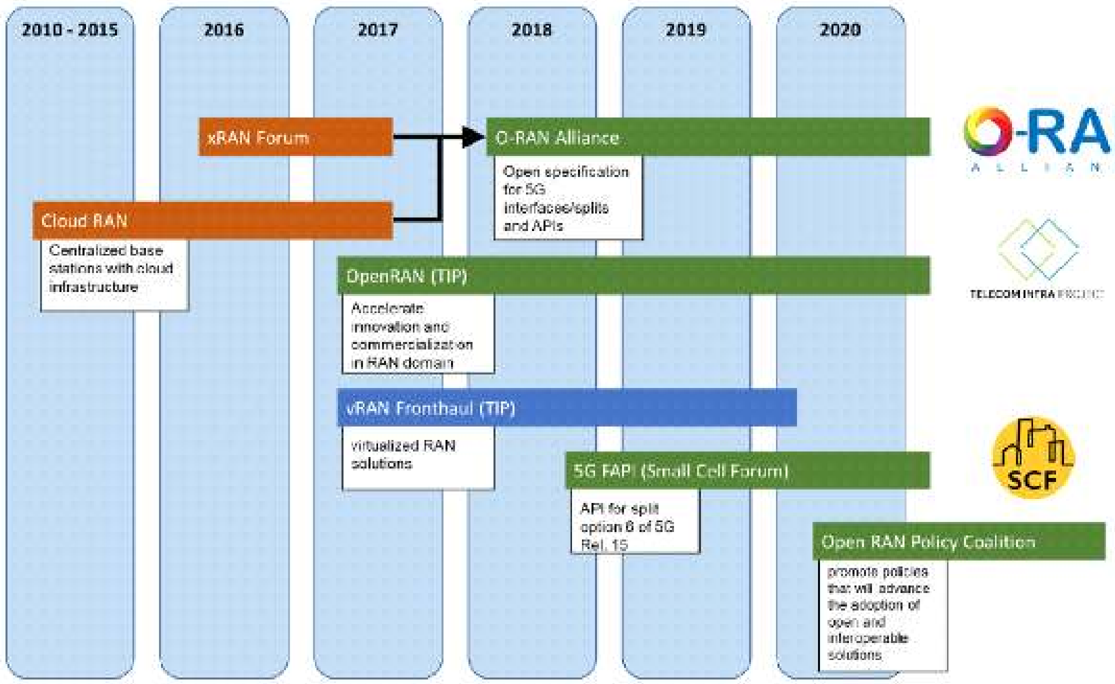

Figure 5. Open RAN related initiatives. Source: AIT (2021)

The O-RAN Alliance is pursuing three main activity streams:[18]

- The specification effort: extending RAN standards towards openness and intelligence;

[17] Source: https://www.o-ran.org/membership.
[18] Source: O-RAN Alliance (2018)

- The O-RAN Software Community: development of open software for the RAN (in cooperation with the Linux Foundation); and

- The testing and integration effort: supporting O-RAN member companies in testing and integration of their O-RAN implementations.

In May 2020, the Open RAN Policy Coalition was formed to promote and advance the adoption of open and interoperable solutions in the RAN and expand the supply chain for advanced wireless.

As for 5G in general, the O-RAN Alliance specification is being released in phases. Alignment between the 5G and O-RAN releases will be required to assure a proper functioning system. In Shanghai, in 2021 the O-RAN Alliance published the "Open" package which included a series of open fronthaul, open transport, open hardware, open stack, open cloud features, testing and integration criteria and guidelines for Open Testing and Integration Centres ("OTIC").[19] By the end of 2021, the O-RAN MVP can be expected to offer an end-to-end solution for the Service Management and Orchestration ("SMO") and the second phase of RAN slicing. Additionally, security and the open cloud API will be enhanced with further updates and new MVP features such as Shared O-RU will be considered for future releases.[20] The use cases that are prioritized for 2021 are: traffic steering; QoS and QoE optimization; RAN slicing and SLA assurance and Massive MIMO optimization.

The above reflects the priorities as set by the operator members of the O-RAN Alliance. The actual development of O-RAN functionality takes place in the Open-Source Community ("OSC"). The OSC publishes two releases every year.[21]

2.2 Towards O-RAN deployment

To support the field deployment of O-RAN functionality, the Test and Integration Focus Group ("TIFG") defines the O-RAN Alliance's overall approach for testing and integration. This includes coordinating the test specifications across all the different Working Groups, as well as the requirements for the OTICs, which are "…vendor-independent, open and qualified physical labs that provide a collaborative, open and impartial working environment to support the wide adoption of O-RAN specifications."

OTICs promote the openness of the O-RAN ecosystem via testing services, lab and field trials, and community events (e.g., speaker sessions, workshops, tutorials)".[22] European OTICs have been approved in Berlin, Madrid, Paris and Torino.[23]

[19] Source: Ibid.
[20] Source: Ibid.
[21] Source: O-RAN Alliance (2021) and the release schedule on: https://wiki.o-ran-sc.org/display/REL/Releases.
[22] Source: O-RAN Alliance (2021).
[23] For a full list of Open Testing and Integration Centers (OTIC), please refer to https://www.o-ran.org/testing-integration.

O-RAN plugfests are organised to support the ecosystem players in the testing and integration of their solutions. In plugfests, different vendors test the interoperability of their products or designs with those of other manufacturers. This facilitates a coordinated global development effort that "…allows for timely advancement of the solutions from the various vendors based on the latest […] test specifications".[24] Two global plugfests have been held, the first in December 2019, and the second in September 2020. Participation in the Global PlugFests more than doubled with 144 corporate participants in the 7 global venues in November 2021.[25] Additionally, OTIC labs host other activities, such as RIC platform trials like the one currently running in Berlin.[26]

Early promotors of Open RAN have included new entrant operators, such as Rakuten, an entrant operator in Japan, who have used partners with a background in radio technology (like NEC), and other partners with virtualisation experience to be applied in the CU/DU to bring O-RAN products to market with a relatively short delay relative to the 3GPP timeline. Other early adopters include DISH in the United States, which completed its first fully open RAN-compliant network communication in December 2020 with vendors MTI, Mavenir and Nokia; and a European entrant in Germany, 1+1 Drillisch, which is using technology developed by Rakuten and referred to as the Rakuten Communications Platform ("RCP"). Rakuten also created a subsidiary, Symphony, for the OpenRAN business which uses Accenture and Tech Mahindra as systems integrators on Symphony projects.

A survey of existing operators by Analysys Mason suggests that the biggest risk for Open RAN is not being ready before these operators deploy virtual 5G RANs at scale: 15% said they will deploy a virtual RAN for their macro 5G network in 2020-2022, 45% of the respondents in 2023-2024 and 40% in 2025-2026.

These timelines may change, however, to be successful, the O-RAN Alliance initiative will need to ensure that commercial Open equipment is available for integration and deployment within the next 5 years.

2.3 Open RAN in Europe

In early 2021, a group of European operators - Deutsche Telekom, Orange, Telefónica, Telecom Italia (TIM) and Vodafone - announced a Memorandum of Understanding ("MoU") to support the rollout of Open RAN as "the technology of choice for future mobile networks to the benefit of consumer and enterprise customers across Europe".[27] According to the news release: "Under the MoU, the signatories published technical guidelines in mid-2021 to help new and existing vendors develop software and hardware that is interoperable. The purpose is to foster a competitive Open RAN

[24] Source: https://www.vodafone.com/news/technology/europe-urged-build-open-ran-ecosystem.
[25] Source: O-RAN Alliance (2021) and the blog at: https://www.o-ran.org/blog/tag/%23Plugfest.
[26] Source: "ONF and Deutsche Telekom Demonstrate Fully Disaggregated Open RAN with Open RIC Platform", https://opennetworking.org/news-and-events/press-releases/onf-and-deutsche-telekom-demonstrate-fully-disaggregated-open-ran-with-open-ric-platform/
[27] Source: https://www.vodafone.com/news/technology/europe-urged-build-open-ran-ecosystem.

ecosystem, promoting openness and flexibility. The signatories will be expanding these initially proposed requirements to include intelligence and automation proposals".[28]

In addition: "the Open RAN MoU group of signatories agreed to further help advance various aspects of the Open RAN ecosystem through a set of actions. These include the active participation in Open RAN focused R&D projects, the support for edge computing initiatives in Europe, an uninterrupted renewed attention to compliance with evolving European security initiatives, and ever-greater interworking between industry communities, such as TIP and the O-RAN Alliance, and standard bodies like 3GPP".[29] The above implies a threefold set of objectives: (1) to support the standards process; (2) to enable the entry of new vendors, to promote competition; and (3) to promote the benefits of Open RAN to policymakers and seek funding to support its development.

2.4 Assessment

The next generation of mobile technology is likely to incorporate several important innovations which have their origins in various initiatives, in different bodies, and for different motivations. Many of these are driven by the need to develop networks for the future which are more flexible and easier to scale, replace, have better performance, consume less energy, have lower costs, and by the concerns of operators to change the supply chain so that there are more competitors and greater diversity. The consequence of this is that 5G in its mature form can be expected to represent the most fundamental advance in mobile networks since at least 2G.

Many of these innovations, such as virtualisation, software-defined networks, cloudification, or the use of AI/ML, already co-exist or could co-exist in the traditional closed RAN architecture in which the only open interface is the backhaul interface between the RAN and the core network and where network equipment is supplied by the same group of established suppliers. These innovations, many of which have been developed or advanced with the involvement of the traditional suppliers over recent years, would each deliver significant benefits even if they were not to be incorporated within an Open RAN architecture.

However, Open-RAN represents a further and potentially revolutionary development which may be realised in 5G. By opening up (i.e., standardising) the interfaces within the RAN, such as the open fronthaul interface, mobile operators are seeking to change both the way they deploy and operate the RANs in their networks, and how the supply chain supports the RAN operation itself. If successful, this could have profound consequences for the prospects of both individual firms and the industry, in the same way that the decision to standardise and open the interface between the RAN and the CN had profound consequences for the industry in the 1990s.

The case for Open-RAN as means of enabling entry or expansion by new suppliers into the supply chain and allowing operators to mix and match network components in a much more flexible way has been supported by network operators around the world (and by other participants such as the TIP and

[28] Ibid.
[29] Ibid.

ORPC) for several years. However, it is less clear that Open RAN aligns fully with the interests of the traditional equipment suppliers and progress in standardisation within 3GPP does not seem to have progressed as quickly or urgently as some operators wish. This may be partly because the number of participants involved in the 5G 3GPP standardisation process is far greater today than was the case when previous generations of technology were being developed. Being consensus-driven, the process of agreeing is, therefore, more complex and may take longer than before.

The O-RAN Alliance was established in 2018 as a response to this concern. Rapid progress is important if the commercial delivery of Open-RAN is to be aligned with the other initiatives, which form part of the overall 3GPP 5G release programme, and with the investment cycle of the industry itself. Otherwise, individual operators could face difficult choices between delaying the replacement of their RANs and realising other benefits from 5G technologies, which are already mature, or proceeding with 5G without Open RAN, with a risk that this undermines its long-term commercial prospects and commitment by suppliers to Open RAN. At this stage, it appears that Open RAN equipment and services will need to be available by the middle of this decade if they are to be incorporated into the new virtualised 5G RAN deployments that many existing operators are planning. This is not unrealistic given that many operators are already deploying Open RAN sites at a small scale in 2021/2.

Indeed, the O-RAN Alliance has made significant progress since 2018. They may have been assisted in Europe and the US by decisions made by Governments in both regions to require the removal of Chinese equipment from existing networks and/or to prohibit the use of Chinese equipment in 5G networks, including RANs. The motivation for and benefits of Open RAN does not depend upon whether any particular vendors are allowed to supply equipment to operators, but the exit of Chinese suppliers has put further emphasis on the need to diversify sources of supply, reduce dependency on a single supplier, and to promote competition between those suppliers that remain available in Europe and the US. The realisation that decisions taken by policymakers, rather than by the industry, may have led to a less competitive and less resilient supply chain seems to have prompted policymakers in Europe and the US to take a more active interest in the development of Open RAN as a means of mitigating these effects.

Currently, Government involvement takes several forms. One form might be described as oversight to identify where problems may arise which require intervention and/or to validate claims being made to policymakers by the proponents of Open RAN. For example, in June 2021, the US NTIA's Institute for Telecommunication Sciences ("ITS") announced that it will procure Open RAN equipment for testing. ITS is seeking equipment used in Open RAN 4G and 5G networks, as well as Virtualised RAN (vRAN) software and RAN automation software to deploy in its Communications Research and Innovation Network to evaluate performance, inter-vendor interoperability, and standard maturity compared with established RAN technologies".[30] Similarly, in Japan, the Government has announced it is setting up a wide-area experimental network to test 5G O-RAN. This is being led by Japan's Ministry

[30] Source: https://www.ntia.doc.gov/press-release/2021/ntia-s-institute-telecommunication-sciences-announces-plan-procure-open-ran.

of Internal Affairs and Communications. NTT Docomo, Rakuten Mobile and NEC will be conducting the tests.[31]

Another form involves public funding of pre-commercial activities. For example, the Federal Ministry of Transport and Digital Infrastructure ("BMVI") in Germany awarded € 32 million in subsidies to major manufacturers, operators testing firms and systems integrators to expedite Germany's development of Open RAN technology and 5G inventions.[32] In June 2021, the launch of SONIC Labs was announced, a joint testing facility for Open RAN between Ofcom and Digital Catapult and partly funded by the UK government. It is part of the government's 5G Supply Chain Diversification strategy announced in 2020.[33] The UK Government is also funding an initiative under the heading: "Future RAN: Diversifying the 5G supply chain" with a budget of approximately £ 33.5 million, across 15 projects. In December 2021 the competition winners were announced, these include the operators BT, O2, and Vodafone; cloud providers: AWS and Microsoft; technology providers: Amdocs, Cisco, Intel, Thales, and Toshiba; the prominent O-RAN players: Parallel Wireless and VIAVI; integrator Capgemini; a wide range of other companies, a total of 30$^+$ companies; as well as the Universities of Ashton, Bristol, Coventry, Edinburgh, Leeds, Surrey, Warwick, and York.[34] To date, funding by the European Commission for Open RAN (outside of wider Horizon 5G R&D programmes) appears limited, despite calls from European operators for more public funding to be made available.

Governments are also involved in assessing the security implications of Open RAN technologies, often alongside more wide-ranging assessments of the critical telecoms infrastructure which all Governments are increasingly engaged in. Recently, for example, the European Commission has coordinated an assessment of Open RAN security issues by the NIS Co-operation Group.[35] The issues are complex because the open fronthaul interface potentially increases the vulnerability of the network to unauthorized penetration, but other features, such as the use of AI/ML to anticipate threats and the ability of multiple vendors to develop security solutions, could also mean that Open RAN is a more secure environment than closed systems.

It should be noted that the O-RAN Alliance and its members are already undertaking significant work on security issues. A 2021 O-RAN White Paper states: "O-RAN also shares common security risks with virtual and cloud-based deployments due to use of open-source software, white-box hardware and the multi-party relationship between the operator, cloud provider and system integrator".[36] The Security Focus Group ("SFG"), as part of the O-RAN Alliance activities, is following 3GPP security design practices and industry best practices "to identify security requirements and solutions that enable O-RAN to deliver the level of security expected by 5G network operators and users".[37] A 5G Americas White Paper on "Security considerations for the 5G era" states that the transition towards open and cloud-native networks also provides benefits: "open, interoperable interfaces available deeper within

[31] Source: https://mobileeurope.co.uk/press-wire/16364-japanese-government-and-vendors-prepare-to-test-5g-o-ran-in-2022.
[32] Source: https://mobileeurope.co.uk/press-wire/16300-in-worst-case-scenario-open-ran-is-not-secure-german-federal-office-study.
[33] Source: https://www.digicatapult.org.uk/how-we-can-help/what-we-offer/programme/sonic/.
[34] Source: https://www.gov.uk/guidance/future-ran-diversifying-the-5g-supply-chain-competition-winners.
[35] Source: https://digital-strategy.ec.europa.eu/en/library/cybersecurity-open-radio-access-networks.
[36] Source: O-RAN Alliance, 2021.
[37] Source: O-RAN Alliance, 2021.

the RAN infrastructure introduce capabilities for isolating controls, greater observability, and independently generated operational telemetry. Those interfaces provide modularity, which could potentially allow more granular security attestation as standards and best practices continue to evolve in this space. They can also reduce dependencies on unique software capabilities, making it less risky to update software to apply fixes".[38] In a recent White Paper issued under the Open RAN MoU by Deutsche Telekom, Orange, Telefónica, TIM and Vodafone, the importance of Open RAN security is emphasised, with reference to the work by the SFG and the aim of the MoU group of MNOs to ensure a fit with the EU 5G Cybersecurity Framework.[39]

Finally, the UK Government has sought to promote Open RAN by publishing a set of 'principles' which it expects suppliers and operators to adhere to.[40] The intention is that these principles drive further discussion across governments and industry over how best to support the maturation of Open RAN. This marks a more interventionist approach, at least by the UK Government, in terms of showing a clear intent of how it wants to see the RAN equipment ecosystem to develop. The UK Government has also set a joint ambition with the MNOs for 35% of traffic in the UK being carried over Open RAN by 2030.[41] It is not clear how this ambition will be applied or enforced.

To date, the most significant action taken by the O-RAN Alliance itself appears to be, first, the decision to specify and commit to the eCPRI 7-2x interface for the open fronthaul. This provides the clarity that other firms require if they are to be expected to invest in developing products and services for Open-RAN and appears likely to be eventually incorporated into the 3GPP standards. Furthermore, the O-RAN Alliance has also overseen the rapid development of testing and integration platforms around the world, providing an opportunity for developers and suppliers to collaborate and test prototypes in standardised environments.

The evidence suggests that these actions have unlocked significant activity, including by new firms or firms from adjacent industries, which have not previously participated in the mobile network, and supply chain. The traditional equipment suppliers, including Nokia and Ericsson, are active participants in the Open RAN fora and appear to be making positive contributions.[42] Other suppliers of O-RAN services and participants in the work include Mavenir, Parallel Wireless, Rakuten Symphony (formerly AltioStar), Qualcomm, NXP and many other firms.

European operators will benefit from diversity and competition in the supply chain that results from Open RAN regardless of whether the new entrants in the supply chain are European in origin. However, European (and US) policymakers can be expected to have an interest in promoting the participation of firms from within their region. US policymakers have argued that Open RAN provides

[38] Source: "Security considerations for the 5G era" 5G Americas (2020).
[39] Source: "Open RAN Security White Paper" at: https://static1.squarespace.com/static/5ad774cce74940d7115044b0/t/623adef88d4ea05aae841f40/1648025338041/Open+RAN+MoU+Security+White+Paper+-+FV.pdf
[40] Source: https://www.gov.uk/government/publications/uk-open-ran-principles/open-ran-principles
[41] Source: https://5gobservatory.eu/uk-government-targets-35-of-traffic-over-open-ran-by-2030/#:~:text=The%20announcement%20came%20in%20a,by%202033%20was%20also%20set.
[42] For instance, Nokia contributed the eCPRI7-2 specification, see: https://www.nokia.com/blog/making-sense-of-oran-and-vran-part-one/.

an opportunity for the US to re-enter the mobile equipment supply market, which, as explained earlier, in recent years, has been dominated by European suppliers in the form of Ericsson and Nokia, and by Chinese vendors.

A 2021 Analysys Mason study considered the position of European firms in relation to non-European players across the components of the value chain. It showed:

- a *strong position* for system integrators (Capgemini, Atos, Reply), and testing (Rhode&Schwarz, Spirent);

- a *moderate* position for the radio frequency frontend (NXP), RAN software (Capgemini, Nokia), RAN Intelligent Controller (Capgemini, Ericsson, Nokia), Management & Orchestration (Ericsson), and Enterprise Services (Nokia, Cellnex); and

- a *weak* position in GPU (NXP, ARM), Specialised silicon chipsets (NXP), and foundry (NXP). This is an area where other European objectives in relation to semiconductors may also have consequences for European firms in the Open supply chain in the long term.

The report also shows SMEs active in Open RAN for each category and identifies Infineon, Kalray, ST Micro, and Bosch as being capable of addressing key Open RAN challenges.[43]

Individual operators or groups of operators are also taking their initiatives. Within Europe, we referred above to the MoU that has been concluded amongst Europe's largest operators. The aim of this initiative appears to be to provide potential suppliers of Open RAN equipment and services with the confidence to invest in their development now, knowing that the major operators in Europe will have similar technical requirements and will provide a market opportunity of significant scale. It also allows the major operators to engage with policymakers in a coordinated and likely more effective fashion across a range of issues. However, individual operators are, of course, also following their commercial activities at the same time:

- For example, Vodafone claimed to be the first operator in the UK to switch on a live Open RAN site in the summer of 2021 and announced Samsung and NEC as the vendors that will support its European deployment.[44] Vodafone has also published a white paper proposing a new collaborative model for the integration and acceptance testing of Open RAN network components before commercial deployment by operators.[45]

- In June 2021, Deutsche Telekom announced that it had switched on its 'O-RAN Town' deployment in Neubrandenburg, Germany. O-RAN Town is a multi-vendor open RAN network

[43] Source: As reflected in the paper "Building an Open RAN ecosystem for Europe" by Deutsche Telekom, Orange, Telecom Italia (TIM), Telefónica, Vodafone.
[44] Sources: https://www.ft.com/content/0055201f-086c-439a-a252-4f07dbf23b62; https://telecoms.com/510095/uk-surfers-get-openran-based-connectivity/; https://telecoms.com/510126/big-wins-for-samsung-and-nec-as-vodafone-reveals-openran-suppliers/.
[45] Source: https://www.vodafone.com/news/technology/vodafone-driving-greater-efficiency-open-ran.

that will deliver Open RAN-based 4G and 5G services including the integration of massive MIMO (mMIMO) RUs. Vendors include Dell, Fujitsu, Intel, Mavenir, and NEC.[46]

- Telefónica and NEC Corporation are to conduct Open RAN pre-commercial trials in Telefonica's four core global markets: Spain, Germany, the UK and Brazil. NEC will serve as the prime system integrator to implement and conduct trials of multi-vendor-based Open RAN solutions.[47]

- Orange France has launched its Open RAN Integration Center in Châtillon, near Paris, to test and validate equipment for its suitability for Open Radio Access Networking. Among the partners working with Orange is wireless system maker Aw2/Serma, radio product supplier Benetel, service management orchestrator Cellwize, server maker Dell, processing giant Intel, and test and validation specialist Keysight.[48]

- Telecom Italia Mobile started field tests of Open RAN solutions in Faenza and Matera. The RAN software components were supplied by JMA Wireless and Mavenir, radio frequency equipment came from Microelectronics Technology ("MTI"), and Dell Technologies supplied the hardware, while Cisco was responsible for transport and Italtel for systems integration.[49]

- NTT DOCOMO agreed with 12 companies, namely Dell Technologies Japan Inc., Fujitsu Limited, Intel K.K., Mavenir, NEC Corporation, NTT DATA Corporation, NVIDIA, Qualcomm Technologies, Inc., Red Hat, VMware K.K., Wind River and Xilinx, Inc. to cooperate towards the "5G Open RAN Ecosystem" to globally accelerate Open RANs, and help enable flexible network deployment to serve the diverse company and operator needs in the 5G era.[50]

There is, in other words, no shortage of pre-commercial trials and small-scale deployments of Open-RAN technology by operators and participation by vendors, for many of whom Open RAN provides an opportunity to enter the RAN network equipment supply chain for the first time. However, we note that European operators are often partnering with non-European or with more established vendors such as NEC, presumably because they consider that they are best placed to meet their immediate needs.

There is also significant interest in and support for the objectives of Open RAN amongst policymakers, both in Europe and in the US, but it is not always clear whether the actions taken by Governments complement or substitute for the various initiatives that are being taken by the O-RAN Alliance or by the industry itself. There is also a risk that actions by Governments in different regions that seek to promote trade interests will neutralise each other rather than advance the development of the global 5G supply chain. It is not obvious that individual operators should be concerned about the nationality of a new entrant or should be expected to compromise their commercial interests to support the

[46] Source: https://www.telekom.com/en/media/media-information/archive/telekom-switches-on-o-ran-town-in-neubrandenburg-630566.
[47] Source: https://www.mobileeurope.co.uk/press-wire/16079-telefonica-and-nec-to-pilot-open-ran-live-in-four-key-locations.
[48] Source: https://mobileeurope.co.uk/press-wire/16261-orange-opens-first-lab-in-france-dedicated-to-testing-and-developing-open-ran.
[49] Source: https://telecoms.com/511869/tim-increases-open-ran-footprint-again/.
[50] Source: https://www.docomo.ne.jp/english/info/media_center/pr/2021/0208_00.html.

development of a local supply chain if this means delaying the benefits of Open RAN in Europe or accepting inferior products.

It is not surprising to find that the largest mobile operators are the leading participants in the O-RAN Alliance and other initiatives, including in Europe. That said, new entrant operators, like Rakuten in Japan and Dish in the US, have also been early adopters of Open RAN architectures as they deploy new networks. It will be important to ensure that the benefits of Open RAN will be available to all firms, regardless of size, and that efforts to increase competition in the upstream supply chain do not have any unintended adverse consequences for competition in the mobile services markets which they support. We consider this issue further in the next section.

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THE ECONOMIC IMPACT OF OPEN INTERFACES

3. THE ECONOMIC IMPACT OF OPEN INTERFACES

In the previous section, we have discussed why and how the Open RAN concept was developed and some of the various actions being taken to implement it, especially focussing on the opening of the fronthaul interface. If successful, the development of Open RAN, and particularly the introduction of an open fronthaul interface, will affect the structure of mobile markets and how market players compete, leading to different market outcomes in terms of network equipment prices, investment in new infrastructure and innovation. We consider these issues further in this section.

We discuss the social welfare impact of wide adoption[51] of Open RAN compared to a *status quo* situation where it would not be adopted, and operators would continue deploying networks for which the entire RAN would be supplied by a single supplier. We consider more specifically the impact of Open RAN in terms of:

- *Downstream competition*: What are the likely effects of the adoption of Open RAN by mobile operators on competition in the downstream market? Some of the effects may depend on how the upstream (supplier) market is affected by the development of Open RAN. Others may depend on how the new technology affects mobile operators' competitive strategies.

- *Investment in network deployments and upgrades*: What are the possible effects of the adoption of Open RAN on investment by mobile operators in new mobile technologies, for example, for the deployment of 5G?

- *Innovation in equipment and services*: What are the likely effects of innovation in new equipment or new services in the upstream supplier market and the downstream operator market?

We start by developing an economic framework in the next section. The general idea is that the economic impact of Open RAN stems from a change from a (relatively) closed market organisation to a (relatively more) open market organisation. This change of market organisation, towards more openness, has repercussions on the upstream and downstream markets which are discussed in the next sections.

3.1 From a closed to a more open market organisation

The adoption of Open RAN may affect the mobile industry because it will involve changes in network costs or the performance of the infrastructure. For mobile operators, the new technology can be costly to roll out than existing technologies or it can be more or less efficient (e.g., in terms of radio performance, energy footprint or security aspects), which can affect firms' conduct and market outcomes. However, the adoption of Open RAN may also affect mobile markets because this new

[51] Some telecommunications operators have stated the objective of widely adopting Open RAN. For instance, Orange has declared that by 2025, any equipment that it buys in Europe will have to be O-RAN-compliant. See the press release at: https://www.orange.com/en/newsroom/press-releases/2021/orange-inaugurates-first-laboratory-france-dedicated-open-ran

technology is more "open" than existing technologies, which is likely to affect the market structure and the competitive conduct of market players.

We consider the introduction of the Open RAN technology as representing a change of market structure in the upstream supplier market, from a situation where traditional integrated equipment suppliers, like Ericsson, Nokia, or Huawei, sell complete, end-to-end systems to mobile network operators, who then sell mobile communications services to end users, to a situation in which suppliers sell specific components and operators can mix and match components from different Open RAN vendors which interwork with each other across open interfaces, including but not limited to open fronthaul.[52]

This change in the market structure in the upstream supplier market is illustrated in Figure 6 below. A situation where equipment suppliers sell end-to-end systems corresponds to what we call a *closed market organisation* (on the left-hand side of the figure). When they sell individual components, which can be mixed and matched by mobile operators, we have an *open market organisation* (on the right-hand side of the figure).[53]

Figure 6: Closed versus open market organisations.

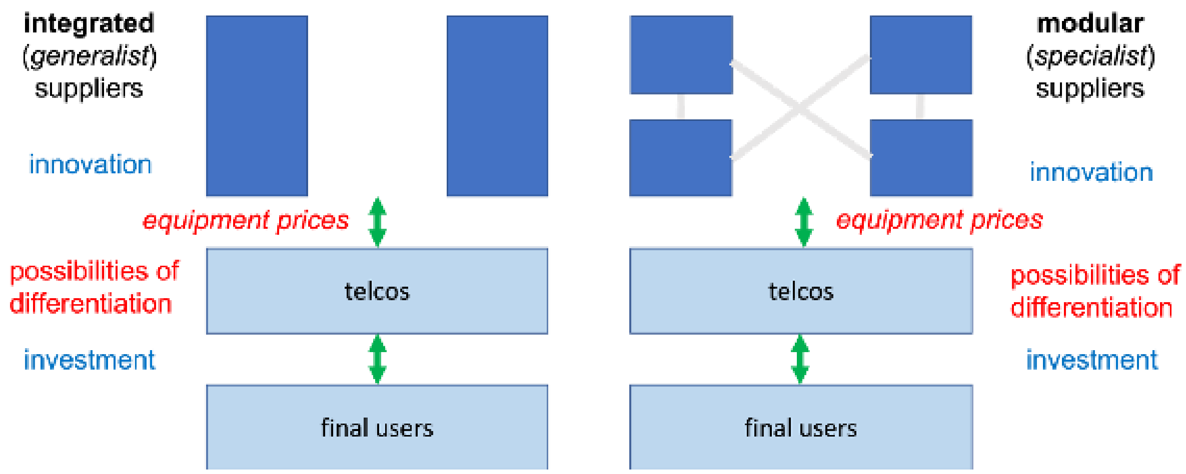

Figure 6 shows systems consisting of only two (network) components, but there can, of course, be more than two components in a complete system. In an open market organisation, some firms may specialise in selling a specific component, whereas others may offer more than one component or

[52] Our interpretation is in line with the vision proposed in the report "Building an Open RAN Ecosystem for Europe" published by Deutsche Telekom, Orange, Telecom Italia, Telefonica and Vodafone in November 2021, where they contrast the closed interfaces of traditional RAN technologies to the open and disaggregated interfaces of Open RAN. This report is available, for example, at: https://www.vodafone.com/sites/default/files/2021-11/building-open-ran-ecosystem-europe.pdf

[53] We adopt the terminology proposed by Farrell et al. (1998). See Farrell et al. (1998) for a general economic analysis of closed and open market organisations.

even all of them. Generalist firms selling complete systems may thus coexist with specialists selling specific components. We saw this with 2G in Section 2, where we noted that firms like Nokia or Ericsson supplied both the core network and the RAN whilst other firms supplied only the RAN. Firms may also differ in size, with smaller firms and larger firms, as we are seeing with the entry of new firms supplying Open RAN components which was discussed in Sections 2.2 and 2.3. What matters and defines the open market organisation is the ability of client firms (the MNOs) to mix and match components from different vendors.

We have already noted that mobile operators already mix and match some network elements and that multi-vendor deployments are common. However, we consider that the Open RAN technology gives, and is intended to give, more opportunities to mix and match network components from different suppliers and that this is facilitated by open interfaces such as the open fronthaul interface.[54] Our framework illustrated in Figure 6 above thus aims to contrast two situations: one where the upstream (supplier) market is still relatively closed, and one, with the development of Open RAN, where it is relatively more open. The economic impact of Open RAN stems from this change in the market organisation in the upstream part of the value chain.[55] We describe both types of organisations in more detail below using the terminology of Farrell et al. (1998) and the related literature (see also the summary Table 1).

3.1.1 Closed market organisation

In a closed market organisation, firms are 'generalists'. They combine the different, complementary components necessary to offer complete, end-to-end systems. A generalist firm can develop all components in-house, but it may also outsource the development of some of them to third parties. In all cases, the generalist firm integrates the different components into a complete system. Thus, the firm possesses the technological and managerial capabilities necessary to integrate all components. Generalist firms then compete in selling complete systems to downstream firms or to customers.

In the mobile industry, the *status quo* situation corresponds to a (relatively) closed market organisation in which traditional equipment vendors like Nokia or Ericsson sell end-to-end proprietary systems to MNOs.[56] In this type of market organisation, the value chain is closed to outsiders. Only integrated firms can provide a specific component for their system (it does not preclude them from outsourcing the development of a given component). Entry into this type of market is only possible through the provision of a complete system, creating high barriers to entry. Over the last couple of decades, the entry of new integrated equipment suppliers has been rarely observed in the mobile industry, with the Chinese vendors, Huawei and ZTE, being the exception.

[54] Interfaces can be standardised and still closed. For instance, the interface X2 between small-cell and macro-cell base stations is standardised by 3GPP. However, to fully interoperate small-cell and macro-sell base stations, an operator is obliged to buy them from the same supplier.

[55] One could argue that this change of market organisation, from closed to open, may be valid for other innovations, like virtualisation. Our point is not to say that our framework applies only to Open RAN. Our view is rather that it is the relevant framework to analyse the economic impact of Open RAN.

[56] Note that this is a simplification. Network operators can acquire other components (e.g., value-added services) from other vendors.

As noted earlier, many of the innovations associated with 5G (such as virtualisation, software defined radios, cloudification or the use of AI/ML could) could potentially be delivered by a closed market organisation. This could deliver significant benefits, but operators would be required to obtain these capabilities from one supplier, at least so far as the RAN element is concerned.

3.1.2 Open market organisation

In an open market organisation, "specialists" develop individual components that are combined *ex-post* through the market. However, some firms may produce more than one component or may be active over the whole spectrum of components (i.e., operate as generalists). What characterises this market organisation is that a pure specialist, selling only one component, can be active in the market. The client firms – the MNOs in our case – can thus mix and match components from different vendors thanks to open and standardised (interoperable) interfaces between the different components.[57] For example, with Open RAN, the CU and the DU can be supplied by different vendors (given the open midhaul interface), as can the DU and the RU (given the open fronthaul interface). For the DU itself, the hardware and software components can originate from different suppliers. Thus, the RAN is effectively being unbundled into its constituent functions and components, allowing an operator to source each from a different vendor.

System integration (i.e., the combination of components into a complete system) can be realised by the user, i.e., the MNO. It can also be outsourced to a third-party integrator, which will be essential for MNOs that do not have the skills or scale necessary to undertake integration in-house efficiently. System integration also happens in a closed market organisation, but it is internalised by the vendor. Thus, Open RAN involves moving functions and the associated costs between players in the supply chain without necessarily reducing or increasing these costs. We will discuss in more detail below the implications for the cost structure of mobile operators.

In this type of market organisation, specialist firms compete in selling their components. Of course, traditional RAN vendors can still be active under an open market organisation. Traditional vendors like Ericsson and Nokia have joined the O-RAN Alliance, while Huawei has not, though it is active in Open RAN generally.[58] But an open market organisation may also stimulate the entry of new players, as we have already seen with the entry of firms (or expansion of existing participants in the mobile supply chain into new areas of activity) including Samsung, Parallel Wireless, Altiostar (now part of Rakuten Symphony), Intel, and Mavenir in the provision of Open RAN components and services, as discussed in the previous section.[59] Since entry is possible at a specific stage of the value chain by providing only a single component, barriers to entry are lower with this type of market organisation than with a closed market organisation.

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[57] Note that, while interfaces are open and standardised, the individual hardware or software components are typically proprietary.

[58] See M. Lorre, "Open or closed, RAN vendors face a 2020s squeeze," 21 January 2021, https://www.lightreading.com/open-ran/open-or-closed-ran-vendors-face-2020s-squeeze/a/d-id/766804

[59] See, "Parallel Wireless heads league table for open RAN vendors," 11 June 2021, https://www.capacitymedia.com/articles/3828820/parallel-wireless-heads-league-table-for-open-ran-vendors

The following table summarises the key differences between closed and open market organisations.

Table 1: Characteristics of closed and open market organisations.

MARKET ORGANISATION	CLOSED	OPEN
Firms are…	*Generalists*: they offer complete, end-to-end systems to their customers	*Specialists*: they develop specific components, which are integrated *ex-post.* *Generalists* can also operate, offering end-to-end systems
Interfaces between components	Proprietary	Open
Integration of components into a complete system	Done in-house by suppliers of complete systems	Done by the user or outsourced to a third-party integrator
Choice set for customers	Customers can choose between different complete systems	Customers can mix and match components from different suppliers to compose their own system
Barriers to entry (*ceteris paribus*)	*Higher*: entry is possible only by offering a complete system	*Lower*: entry is possible by offering a specific component

3.2 Impact on downstream competition

We will now discuss how the adoption of Open RAN can affect competition in the downstream mobile market.

As we will argue in more detail below, the change from a closed to an open market organisation may affect upstream firms' costs, and to the extent that these cost changes are passed through, this will affect the prices of their products (in our case, mobile RAN equipment). However, the change in market organisation may also affect the way upstream firms compete, thereby impacting input prices. Finally, the change of the type of market organisation, from closed to open, may affect the possibilities of differentiation for the downstream firms (the MNOs), which in turn may affect the variety and the price levels of services proposed to end users.

We first discuss how the change in market organisation may affect competition in the upstream supplier market and then describe how it can affect the possibilities of differentiation in the downstream operator market. We summarise the main conclusions from our analysis at the end of the section.

3.2.1 Price competition in the upstream supplier market

In a given market, the prices for products and services reflect the production costs and the intensity of competition between market players. Therefore, the change in the type of market organisation, from closed to open, may affect prices in the upstream equipment market through two different channels: First, through changes in the cost structure, which would be passed through into the input prices charged to the downstream firms, and second, through changes in the competitive behaviour of market players.

Changes in cost structure in the upstream market

An open market organisation is cost-efficient if no integrated supplier is best at providing all individual components. In this case, since all components are available on an individual basis, users can purchase each component from the most efficient supplier, which minimises the cost of the complete system. For instance, assume that there are two components, A and B, to compose an entire system and two integrated firms, 1 and 2, which produce both A and B. Firm 1 is the most efficient in producing component A, whereas firm 2 is the most efficient in producing component B. With a closed market organisation, downstream firms must buy A and B from the same firm. By contrast, with an open market organisation, they can buy component A from firm 1 and component B from firm 2, resulting in a less costly system. The same reasoning applies to quality: in an open market organisation, a downstream firm can pick each component from the highest quality provider. The higher possibilities of entry under an open market organisation (due to lower barriers to entry) can further reinforce the cost advantage of this form of organisation. In particular, 'specialists' may be active in other markets, and therefore, achieve large economies of scale and scope across different markets. Cloud service providers are one example, and so are suppliers of IT hardware, both of which are relevant to the deployment of 5G.

However, an open market organisation may also be cost-inefficient compared to a closed market organisation for different reasons.

Constrained performance

First, the literature suggests that open systems can constrain performance and hence, the quality or performance of components. The first reason is that the different components composing the system are highly complementary and a system may be more efficient when all components are designed jointly by a single firm, perfectly internalising these complementarities. For example, computer software can be optimised for specific hardware, and the hardware can also be designed to improve the performance of the specific software (as in the case of Apple iPhones or PCs). Another reason why open systems can constrain performance is that open, standardised interfaces between components may not evolve as quickly as proprietary interfaces due to the necessary coordination between all stakeholders in an open market organisation, which can be a complex and time-consuming process. We discussed the delay in 3GPP specifying the fronthaul interface in the previous section and explained that this was one reason why the O-RAN Alliance was established in 2018.

Higher integration costs

Second, with an open system, users bear the integration costs, whereas, with a closed system, it is the supplier that bears these costs. To the extent that there are economies of scale in integration, integration costs will be lower with a closed rather than an open system.

In the case of mobile networks, integration is a complex task, even in an open standards environment. Large MNOs may have the scale and skills to integrate components in-house and achieve the same economies of scale as integrated vendors, although there is no certainty of this and the skills required to integrate software may differ from the skills, which mobile operators have traditionally recruited.[60] Small MNOs may lack the scale or in-house technical capabilities to integrate network components in-house efficiently.

One possibility for MNOs would be to outsource some or all these integration tasks to a third party. Traditional integrated suppliers (e.g., Ericsson or Nokia) could play this role and offer integration and testing services to MNOs. However, these suppliers also offer hardware and software components and may have the ability and incentive to favour their products at the integration stage. This may create a need but also an opportunity for more 'neutral' third-party integrators to emerge, integrating system components for MNOs. Such firms can position themselves as 'neutral' between the equipment vendors and software developers and might also aggregate demand on behalf of MNOs (e.g., act as a buyer's club).[61] Other players in the IT sector could also probably take this role, like NEC.[62]

Outsourcing integration to a third party may not allow smaller MNOs to achieve the same integration costs as large MNOs, as the third party would typically make a margin. In this case, the move to Open RAN could contribute to or exacerbate the disadvantages that smaller mobile operators face due to their relative lack of scale. Thus, policymakers could support collaboration amongst small MNOs for joint procurement of Open RAN and joint testing to allow them to achieve the minimum efficient scale in system integration. Having said this, other developments in 5G, such as cloudification, may work in the opposite direction by reducing the impact of fixed costs in mobile network deployment. We have also seen that new entrants such as Rakuten and Dish, rather than the existing large operators, have tended to be early adopters of Open RAN as they deploy new networks. Thus, the overall effect of 5G or Open RAN on competition in the downstream mobile services market remains ambiguous at this stage.

Vertical inefficiencies

Third, a closed organisation may improve vertical efficiency by achieving the type of benefits usually attributed to vertical integration. This may be because internal transaction costs are lower than external transaction costs. Problems like double marginalisation or hold-up are also typically mitigated

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[60] However, not all large MNOs may follow this road, as the example of AT&T, developed in the Annex of this report, has shown.
[61] See https://www.cellnex.com/gb-en/news/cellnex-uk-awarded-a-10-year-contract-to-deliver-5g-private-network-to-support-businesses-in-basingstoke/.
[62] See https://www.nec.com/en/global/solutions/5g/Blog_Integration_Partnership_Collaboration.html.

or eliminated with vertical integration. The double marginalisation problem arises when firms with market power operating at successive levels in the supply chain each apply a mark-up to their prices. This leads to retail prices, which are too high, to the detriment of consumers and the industry. The hold-up problem happens when a firm must make non-contractible specific investments in its relationship with another firm. The former firm may be hesitant to invest, as it faces a risk of *ex-post* 'hold up', whereby the other firm would be in a strong bargaining position and extract the value from the relationship. Thus, the possibility of holding up can lead to inefficient under-investment. These two market failures arise due to externalities that independent firms do not properly internalise. Vertical integration is a way to fix these market failures, as the merged entity internalises the externalities. Hold-up problems may be particularly significant when new and risky technologies are involved.

Table 2 summarises the possible cost and quality advantages and disadvantages of an open market organisation relative to a closed market organisation.

Table 2: Potential cost and quality advantages and disadvantages of having an open market organisation upstream.

POSSIBLE ADVANTAGES	POSSIBLE DISADVANTAGES
Customers can purchase each component from the most efficient or preferred quality supplier, resulting in a lower total cost or a more optimised complete system.	Performance may be constrained, due to: (i) less than perfect internalisation of complementarities between components; (ii) lower pace of technological progress for open interfaces than for proprietary interfaces.
	Higher integration costs due to lack of economies of scale in integration if integration is done in-house and no third-party integrator can emerge.
	Vertical inefficiencies: risk of double marginalisation and hold up.

Our view is that the three sources of inefficiencies (cost and quality disadvantages) associated with an open market organisation can be mitigated with appropriate contractual arrangements.

Regarding the first type of inefficiency (*constrained performance*), the suppliers of complementary components could coordinate at the R&D stage to internalise the complementarities between their hardware and software components, and therefore, optimise the efficiency of systems based on these components. This appears to be what the interoperability and testing initiatives being undertaken by the O-RAN Alliance and by individual operators are intended to achieve.

Regarding the second type of inefficiency (*higher integration costs*), we have suggested that third parties could specialise in integrating components from different vendors, achieving the same levels of economies of scale as integrated vendors of end-to-end systems. It will be important that the development of the market does not inhibit this.

Finally, for the third type of inefficiency (*vertical inefficiencies*), it is well known in the industrial organisation economic literature that appropriate contractual arrangements (vertical relations) can help fix potential vertical inefficiencies.

We therefore conclude that everything else being equal (in particular, taking market structure and firms' conduct as given), the possible disadvantages of an open organisation that we have identified should be mitigated with appropriate arrangements so that the benefits of Open RAN, accruing from the possibility for an operator to pick the most efficient vendor (in terms of cost and/or quality) for each network component, represent the dominating factor.

Changes in intensity of competition

We now discuss how a change from a closed to an open market organisation can affect the degree of competition in the upstream supplier market. To do so, we use the theoretical economic literature on systems (see, e.g., Matutes & Regibeau, 1988).[63]

We follow the literature by assuming the market structure is given and the same in an open and a closed environment. Under this simplifying assumption, we summarise below the main insights from the literature. In the next section, we consider how the type of organisation (closed or open) can affect entry, and hence, market structure. We then offer our conclusions.

The literature considers markets where end users buy systems composed of complementary components. In a closed market organisation, firms sell complete systems to consumers, but not individual components. In an open market organisation, firms sell only individual components, and users can mix and match the components from different firms to make their system.[64] Finally, in all situations, firms compete (only) in prices.

The literature shows that an open market organisation, where users can mix and match components from different suppliers, tends to *weaken* price competition compared to a closed market organisation (e.g., see Matutes & Regibeau, 1988). The reason is that firms in a closed market organisation face a more elastic demand than in an open market organisation. Since demand is more elastic, competition is more intense, and hence, users pay lower prices.

To understand the intuition for this result, consider a firm in a closed market organisation making a price cut for its complete system. Since the system's price is lower, its demand increases and the firm captures the full benefit of this increased demand since it is the only supplier selling this specific

[63] Note that there are two strands of literature on systems. The first strand of literature focuses on the role of network effects for adoption decisions and competition (see, e.g., Katz and Shapiro, 1994). The second strand of literature deals with the comparison between 'closed' systems and 'open' systems and was pioneered by Matutes and Regibeau (1988), in particular. We focus on the latter strand of literature, as it is the most relevant in our case.

[64] The literature talks about 'incompatibility' when firms sell complete systems, which corresponds to a closed market organisation in our framework, and about 'compatibility' when firms sell individual components and users can mix and match, which corresponds to an open market organisation in our case.

system. Now, consider that the same firm operates in an open market organisation and makes a price cut for one of its system components. The demand for this component increases, of course, and the demand for the other component sold by the same firm also increases since it is complementary. On top of this, the price cut also stimulates the demand for the competing suppliers' complementary components, an effect that is not considered by the firm making the price cut in the first place. The firm making the price cut captures only a share of the total increase in demand, resulting in a less elastic demand than with a closed market organisation. This means that specialists have a smaller incentive to cut prices than generalists[65] and that competition between specialists, in selling components, is less intense than competition between generalists, in selling complete systems.

While consumers may benefit from lower prices under a closed market organisation, they have access to a broader variety of possible systems under an open market organisation. For instance, Matutes and Regibeau consider a market for a good composed of two components, with two competing firms. In this case, the number of available systems equals two under a closed organisation and four under an open organisation. Therefore, from the users' point of view, there is a trade-off between the lower prices that a closed market organisation may entail and the wider variety of systems available under an open market organisation, which allows purchasing a system closer to one's taste and may also contribute to greater diversity and resilience.[66]

Consumers who would buy the same system from the same firm under both types of organisations are unambiguously worse off with an open market organisation since they will pay higher prices for the same system. For the other consumers, the possibility to mix and match components from different suppliers allows them to build a system that fits better with their preferences, which can more than compensate for the higher prices they pay. The overall effect for consumers depends upon how much they value the benefits of being able to mix and match and is therefore ambiguous. In terms of total welfare, the authors find that it is higher under an open market organisation if there are no standardisation costs. The intuition is that firms benefit from an open organisation due to the softening of competition. However, if there are standardisation costs, total welfare can be higher with a closed market organisation.

A common concern with closed systems is that, even though users can benefit from low prices when joining the system, they may be locked-in *ex-post*. For example, if there is an aftermarket for maintenance, upgrades, or complements, the provider may have the ability and incentive to exploit its locked-in customer base *ex-post*. In this case, the good prices obtained by users when purchasing the system could be more than outweighed by the high prices of complementary products and services *ex-post*. This depends on users' ability to anticipate those later costs. Typically, in a consumer market, not all consumers are forward-looking, and the risk of *ex-post* exploitation may be high. By contrast, in a B2B context, we can expect firms like mobile operators to be better aware of the risk of

[65] This is consistent with the famous 'Cournot complement effect' according to which a monopolist selling complementary products sets lower prices than independent monopolists selling these products.

[66] A user chooses the system that gives her the highest utility, the utility depending positively on the match between the system and the consumer's preferences and negatively on the system's price.

ex-post lock-in and, therefore, try to obtain lower prices *ex-ante* in compensation for this risk.[67] However, the ability of MNOs to obtain compensation may depend on their bargaining power *vis-à-vis* the vendors of equipment. In this respect, large MNOs may have more bargaining power and may be able to obtain better outcomes than smaller MNOs.[68] On that basis, the avoidance of higher *ex-post* prices with Open RAN may help to offset some of the additional integration costs which smaller MNOs may otherwise face relative to larger MNOs which we referred to earlier.

Matutes and Regibeau (1988) consider a duopoly market with two symmetric firms. With a higher number of firms, there is another effect at play influencing the comparison between closed and open market organisations. When the number of suppliers increases, the number of systems feasible under an open organisation (n^2 if there are n suppliers and systems consist of two components) becomes much larger than under a closed organisation (n systems). The market, therefore, becomes more 'crowded' under an open organisation, that is, many more systems are available. Consequently, suppliers are less differentiated from each other and competition is intensified. Kim and Choi (2015) and Zhou (2017) show formally that competition can be stronger under an open organisation than under a closed organisation if the number of suppliers is above a given threshold. In Kim and Choi (2015)'s setting, for instance, this threshold corresponds to four firms.

In our context, if we ignore for the moment the changes in market structure that an open organisation could entail (i.e., the entry of new suppliers), the relevant number of upstream suppliers seems to be two (i.e., Ericsson and Nokia if we consider Western companies). Without entry of new suppliers, Matutes and Regibeau's result should apply and a move from a closed to an open organisation may soften competition in the upstream market. In other words, the Open RAN initiative could raise prices for MNOs (relative to a traditional closed interface) unless it is successful in promoting entry into the supply chain.

Hurkens, Jeon and Menicucci (2019) show that the assumption made by Matutes and Regibeau (1988) that the firms are symmetric (i.e., identical) is also crucial.[69] If one supplier strongly dominates the others, in the sense that consumers value its products more than its rivals' products, competition is more intense under an open organisation than under a closed organisation. However, in the context of the equipment supplier market, the assumption of symmetry of companies like Ericsson and Nokia seems reasonable. Therefore, once again, if we ignore for the moment the possible changes in market structure, we would expect a move from a closed to an open organisation to soften competition in the upstream market and for Open RAN to raise prices if there is no additional entry.

Denicolo (2000) shows that, under some conditions, the finding that a move from a closed to an open market organisation tends to soften competition extends to a mixed market structure, where an

[67] This is because operators would typically compare the total costs over the lifetime of an equipment of different offers from vendors, including the initial price, but also future maintenance or upgrade costs. A vendor setting high prices for maintenance or upgrades would thus be obliged to offer low initial prices to be competitive. One limit to this argument is that MNOs may not be able to perfectly anticipate all their *ex-post* needs in terms of maintenance or upgrades.

[68] Note that vendors like Ericsson often operate the network on behalf of the MNOs via outsourcing contracts. This is another way in which the vendor seeks to 'lock in' the MNO.

[69] See also Hahn and Kim (2011) for an analysis of the role of asymmetries.

integrated generalist firm competes with specialists. More specifically, Denicolo shows that, compared to a closed market organisation, an open market organisation, where consumers can mix and match components from different (integrated and non-integrated) suppliers, softens competition if the differentiation between firms' components is not too low.

Finally, note that this literature considers firms selling products to end-users who are final consumers. In our case, the end-users are downstream firms (mobile operators), which compete with one another. Therefore, we may expect the prices of systems and components to also be influenced by the way downstream competition works, which may itself be affected by the prices of upstream inputs. We are not aware of any academic literature addressing this question.

Changes in market structure

Until now, we have taken the number of market players in both types of market organisations as given and equal. However, market entry may differ between the two types of market organisations. More specifically, we argue that an open organisation is more conducive to entry than a closed organisation and that the Open RAN initiative is specifically intended to achieve this, for the reasons developed below.

First, the literature discussed above shows that when the number of upstream firms is small (for instance, in Matutes and Regibeau's setting, with n=2 firms), firms make higher profits with an open than a closed organisation. Therefore, when the number of potential entrants is limited, there should be more incentive to enter with an open organisation. When the number of potential entries is higher, Kim and Choi (2015) show that there can be more entries with a closed rather than with an open market organisation. This is because, in their framework, with four firms or more in the market, firms make higher profits with a closed market organisation as opposed to an open one. Therefore, the entry should be higher with the former type of organisation. Nonetheless, they also show that the number of different systems available to the end-users remains larger with an open market organisation, even without barriers to entry.

Second, with an open market organisation, entry is easier. To enter the market, a new entrant must successfully develop an individual component rather than a complete system. Therefore, entry costs are lower, and we can expect more entry under an open instead of a closed market organisation. In particular, Open RAN allows unbundling of hardware and software components, which may attract entry from specialists already active in other industries, like IT equipment or software, enabling them to realise economies of scale and scope across different industries. Entry with a single component may also represent a 'stepping stone' for a new firm. If successful, the entrant may later expand into other complementary components, and may even, eventually, offer end-to-end systems.[70]

Third, and finally, the literature has shown that incumbent firms may use incompatibility or pure bundling strategies (hence, closed systems) to deter entry from potential rivals (see, e.g., Whinston,

[70] This 'stepping-stone' (or 'ladder of investment') effect has played a role in the downstream telecommunications markets where new entrants have been able to take foot on the market through access provisions, and eventually expand by developing their own network infrastructure (see Cave, 2014).

1990). An open market organisation also has the benefit of preventing this type of anti-competitive strategy, which may otherwise inhibit entry.

To summarise, we expect more entry under an open market organisation rather than under a closed one. Consequently, the upstream market should be more competitive with an open organisation, leading to lower equipment prices and/or more innovation. The number of available systems will also be larger with an open market organisation, allowing mobile operators to choose systems that fit better with their strategies.

However, incumbent suppliers may have the ability and incentive to restrict or delay the entry of new competitors who would otherwise be enabled by Open RAN, for example by bundling, imposing proprietary interfaces or resisting standardisation efforts. Since the consolidated nature of the existing supply market in Europe means that the entry of new players is a pre-requisite for the switch to a more open organisation to lead to a more competitive upstream market, we recommend that policymakers monitor incumbent equipment suppliers' behaviour with respect to Open RAN developments to detect and discourage any potential actions to deter or delay entry.

It will be difficult for policymakers to anticipate what form this conduct would take, so one way to do this would be to establish a body which would arbitrate promptly in disputes between participants in the supply chain if they were to arise. This should mitigate the risk of protracted litigation in courts which might otherwise favour the incumbent suppliers, and which will undermine confidence amongst those who are required to make investments in the new technology.[71]

Identifying the body to perform this function is not straightforward. Some disputes may be highly technical, such as might arise if technical measures are used to limit the functionality available through open interfaces and which are justified on security or other grounds, but which have the effect of making mixing and matching more difficult and favour those supplying bundles of products or services. Other disputes may be procedural, involving a failure to fully disclose information to enable interworking or delays in testing or trials, or inappropriate conduct within standards setting, testing or other organisations. And other disputes may be purely economic, such as supply arrangements with operators which are intended to exclude competitors, State subsidies, or the like. The key requirement of any body is that it can resolve disputes rapidly and therefore remove uncertainty from the market for all participants. This means its decisions must be difficult to appeal, and its jurisdiction must be wide ranging to reflect the possibility that disputes may arise from allegations of unfair conduct in several different fora.

[71] As we have seen in relation to SEP litigation for 3G and 4G standards over recent years, see https://euagenda.eu/upload/publications/untitled-103734-ea.pdf.

3.2.2 Possibilities of differentiation

A wider variety of systems is available to users with an open organisation than with a closed one, since they can mix and match components from different vendors. As we have argued, it means that a mobile operator can pick each component from the supplier with the lowest cost or the highest quality.

The ability to mix and match components from various vendors also enhances the possibilities of differentiation for mobile operators in the downstream market. We may think of differentiation in the quality of service, some providers offering higher quality services, others of lower quality (e.g., premium versus low-cost), depending on the performance of their respective networks. We may also think of differentiation strategies targeting a specific consumer segment or use case by adopting equipment tailored to these segments or cases. The standardisation of mobile technologies may restrain the possibilities of differentiation for operators. Differentiation possibilities can also be limited by the coverage obligations that all operators face.

Service differentiation is beneficial to users as it tends to enlarge their choice sets and allows them to find services that better fit their preferences. A possible downside highlighted by the industrial economics literature (see, e.g., Tirole, 1988) is that differentiation between competing firms tends to soften price competition. This means consumers have access to products or services that better fit their preferences, but the prices they pay for them may be higher.

In this section, we discussed the possible effects of a move from a closed to an open market organisation on the prices of mobile equipment because of the adoption of Open RAN. We have considered two aspects (i) changes in cost structure for the upstream firms; and (ii) changes in competitive behaviour between market players, both upstream and downstream. Regarding the first aspect channel (changes in cost structure), we conclude that an open organisation may lead to lower costs for mobile operators provided there is enough coordination between independent component developers to internalise the complementarities between their components and manage the evolution of open, standardised interfaces and provided third-party integrators emerge, enjoying the same levels of economies of scale as traditional vendors or large operators, so that smaller MNOs are not put at a significant cost disadvantage.

Regarding the second aspect (changes in competitive behaviour), we conclude that, to the extent that a move from a closed to an open market organisation with Open RAN leads to significantly more (sustainable) entry into the upstream equipment supplier market relative to the position today, then equipment prices should decrease due to intensified competition in the upstream market. The new entry may also allow mobile operators to have access to a wider choice of possible systems, increasing their possibilities of differentiation (which may then result in higher prices).

3.3 Impact on investment by mobile operators

In the previous section, we have argued that a more open market organisation allowed by Open RAN should stimulate the entry of new 'specialists', allowing mobile operators to mix and match equipment from different vendors, putting downward pressure on equipment prices. To the extent that an open market organisation reduces equipment prices for mobile operators, it may also stimulate investment.

In mobile markets, network investment typically takes two forms: (i) investment in coverage for a new network technology (such as, when rolling out a new 5G network), and (ii) investment in quality upgrades (such as, for higher speeds, and so on). If investment costs are lower for operators due to lower equipment costs, then their investment incentives are enhanced. Therefore, investment in coverage and/or quality upgrades should be more significant, though it is hard to evaluate the magnitude of this effect or the extent to which it could be attributed to Open RAN rather than other aspects of 5G.

The move towards an open market organisation may also affect the *type* of investment made by operators. Since operators have more possibilities of differentiation in an open market organisation, as they can mix and match components from different suppliers, investment can be realised to better respond to the needs of specific market segments, which would be more difficult to realise in a closed market. In this case, firms invest not only to compete with their rivals in terms of coverage or network quality, but also to enter and compete in specific segments.

3.4 Impact on innovation

In this section, we discuss the possible effects of Open RAN on innovation, both for equipment suppliers and mobile operators. First, we compare innovation incentives in closed and open market organisations. Then, we argue that the move towards an open market organisation may affect the innovation model of operators, with enhanced ability to offer tailored services targeting niche markets.

3.4.1 Innovation in closed versus open market organisation

A move from a closed to a more open market organisation may intensify competition in the upstream supplier market if the entry of new players materialises, as we have discussed above. The first channel through which an open organisation may affect innovation is therefore the intensification of competition in the market. Ofcom (2022) reviews the relevant literature on the relationship between competition and innovation, and in particular, the seminal contribution of Aghion *et al*. (2005). These authors empirically show that there is an inverted U-shaped relationship between the degree of competition and innovation. Starting from low degrees of competition, intensifying competition stimulates innovation. However, when competition is already intense, strengthening it may inhibit innovation. Ofcom (2022) argues that the current level of competition in the upstream supplier market is rather low – with only two traditional suppliers available in Europe today – and so enhanced competition should spur innovation under these conditions.

The second channel through which the move from a closed to an open market organisation can influence innovation is through the impact of the degree of openness of systems on innovation incentives. We argue below that each type of market organisation, closed and open, has relative advantages for innovation.

Advantages of a closed market organisation

In a closed market organisation, upstream firms (equipment vendors) sell complete end-to-end systems consisting of complementary components to downstream firms (MNOs). As noted earlier, as integrated sellers, upstream firms internalise the complementarities between the different system components in their products. Thus, when an integrated vendor invests in R&D to increase the quality or reduce the cost of a given component, it internalises the positive effect on the sales of all its components. By contrast, in an open market organisation, when an upstream specialist invests to increase the quality of its specific component, it internalises the possible increased demand for its component, but not for the complementary components of the rival firms. Therefore, the firm tends to invest *less* in quality-increasing R&D than generalists in a closed market organisation. Joint R&D programs, or more generally coordination at the R&D level may enable specialists in an open market organisation to solve this problem and better coordinate their R&D efforts. However, this may come at the cost of less flexibility or higher transaction costs for the firms involved in this type of organisation.

The second advantage of a closed market organisation is that the firms control the interfaces between the components in their systems. This means that if innovation in some components requires an evolution of interfaces, it can be done swiftly. In an open market organisation, firms would have to coordinate, but this may prove a complex and slow process, particularly with many stakeholders with divergent interests. As noted previously, the slow progress on specifying the open fronthaul interface in 3GPP was one reason why the O-RAN Alliance was first established.

A disadvantage of closed systems is the risk of user lock-in and its possible negative consequences on innovation. Indeed, even with lower performance, an operator may be forced to stick with the same provider due to high switching costs. User lock-in may then reduce the innovation incentive of vendors.

Advantages of an open market organisation

The first advantage of an open market organisation is that users can mix and match components from different vendors. Users can pick each component from the highest quality provider, resulting in systems of overall higher quality. Consequently, innovation incentives of upstream firms, in particular ‘specialists’, are enhanced.

The second related advantage is that an open market organisation facilitates entry. To successfully enter the market and gain market share, an entrant needs to offer a superior or differentiated component rather than a complete system. Since entry costs are lower, innovative entry is likely to play a more important role in shaping the competition in the upstream supplier market.

As entry can be achieved with a single component, specialisation in innovation is possible. Firms do not have to accumulate deep knowledge in different fields to successfully enter the market with a complete end-to-end system. For instance, hardware and software involve very different capabilities and skill sets. With Open RAN, one can imagine firms specialising in software without providing any hardware or vice versa, allowing for the entry of new types of technology firms with high levels of expertise in a specific area.

An open market organisation also facilitates innovation by users. In the context of the mobile market, it means that with Open RAN, operators may gain more control over the characteristics of their equipment and their evolution and therefore, achieve a more important role in orienting innovation for new network technologies or services. This may allow operators to better satisfy the innovative needs of their downstream users (such as, the 'verticals'). Doraszelski and Draganska (2006) study situations where firms may face a trade-off between introducing a general-purpose product and a targeted product tailored to meet specific user needs. A trade-off arises because, while targeted users enjoy that the product is tailored to their needs, non-targeted users suffer from a 'misfit'. Doraszelski and Draganska (2006) show that whether firms in equilibrium offer general-purpose or targeted products depends on the fixed costs of providing an additional product and the degree of competition.

Under a closed market organisation, operators may face such a trade-off and end up offering general-purpose services to their users instead of more tailored services. By contrast, under an open market organisation, an operator can tailor its system to respond to specific user needs by selecting the appropriate components, if a wide range of components is available.

Altering a specific component is possible without changing the whole system under an open organisation. This means the operator can upgrade specific components without interacting with its integrated equipment supplier, allowing for faster and more independent innovation. For this reason, an open organisation allows for more experimentation by facilitating simultaneous design experiments (Baldwin and Clark, 1997). It will be less costly for an operator to experiment with new network designs or functionalities by altering only specific system components.

The following table summarises the differences between a closed and an open market organisation regarding innovation.

Table 3: Innovation in closed and open market organisations.

CLOSED MARKET ORGANISATION	OPEN MARKET ORGANISATION
Control of innovation: end-to-end system vendors.	*Control of innovation*: producers of components and/or operators.
Efficiencies: (i) Complementarities between system components are internalised, stimulating innovation in components. (ii) Control of interfaces allows for faster changes.	*Efficiencies*: (i) Users can pick each component from the highest quality provider, resulting in systems of overall higher quality. (ii) Facilitated entry of innovative suppliers through specialisation in innovation. (iii) Enhanced opportunities of experimentation for operators.
Inefficiencies: - Vendor lock-in may reduce innovation incentives of vendors.	*Inefficiencies:* - Complementarities between system components may not be fully internalised by producers of components. - Interfaces may evolve at a slower pace, due to the necessity between independent stakeholders.
Type of innovation: improvement of a general-purpose technology.	*Type of innovation*: tailoring of the technology to meet specific needs, either by specialised suppliers or through innovation by users (mobile operators).

3.4.2 Innovation in open organisations: a change of innovation model

From the discussion above, summarised in Table 3, we conclude that innovation may take very different forms in closed and open market organisations. Under a closed market organisation, innovation concerns mainly a standardised, general-purpose technology aimed at offering services for the mass market, though, of course, firms can also offer more targeted products. However, with an open market organisation, firms have enhanced possibilities to create tailored products or services targeting niche markets. Indeed, the flexibility offered by the Open RAN technologies allows for the delivery of tailored products or services by adapting the network to specific needs or use cases (transport, health, and so on).

Whether there is an incentive to engage in tailored innovation depends on whether there is sufficient heterogeneity on the demand side to justify the development of tailored products or services. Our view is that the digital transformation which is being undertaken in many (if not all) sectors of the economy creates an increasing demand for tailored digital services. In other words, the demand for services is becoming more heterogeneous and differentiated. Open systems allow for more flexibility on the network side and therefore, may be better suited to meet a differentiated demand. Open RAN enhances this network flexibility by allowing operators to mix and match equipment from different vendors.

Since the network services are customised rather than standardised, that is, tailored to the specific needs of their users, we can expect an increase in the value created. The question is then how the value is captured, and by whom. We discuss this question in the next section on business models.

3.5 Impact on business models

Business models describe how value within an ecosystem is created, how it flows, how it is captured, and by whom. Teece (2010) argues that technological innovations often require new business models to succeed in the marketplace and that "*new business models can themselves represent a form of innovation*" (Teece, 2010, p. 176). Firms should not only succeed at developing innovative products or technologies, but they also need to find out the appropriate business model for their innovation.

Innovative technology like Open RAN may be more successful if the operators or other firms can also develop new business models to fully exploit it. We might consider two potential business models for Open RAN (although no doubt others are possible). In one 'pipeline' business model, MNOs adopt Open RAN to offer more tailored solutions to verticals but continue acting traditionally as integrated sellers of communications services. On the other hand, Open RAN represents a technology platform, possibly orchestrated by MNOs. We describe these two business models in turn.[72]

MNOs as integrated sellers of communications services

The first scenario is much like the current situation in which mobile operators remain integrated sellers of communications solutions and purchase inputs from other suppliers to do so (the 'pipeline' business model). However, with Open RAN, mobile operators can then purchase and mix and match RAN equipment from different suppliers in a way which they have been unable to do in the past.

Firstly, this allows them to reduce their costs and improve the performance of their networks by selecting the most efficient suppliers for each network component. Cost reductions and quality improvements are partly passed through to end users in terms of lower prices and/or higher service quality. Therefore, end users (final consumers or client firms) will benefit from Open RAN under this model. This view corresponds to the first scenario proposed in the report "5G supply Chain Market Trends" for the European Commission, "Incumbent players driving 5G",[73] where "*more open interfaces (…) bring new equipment suppliers and lower prices*" for MNOs, but "*revenue opportunities in (…) emerging markets may not be realized because of MNOs' and vendors' comfortable position in the large consumer market*."

However, as we have seen, the flexibility offered by Open RAN also enhances MNOs' ability to develop tailored solutions for specific use cases. This corresponds to the view developed in the third scenario

[72] It is difficult for us to assess which scenario is the most likely. Our objective is to show here that Open RAN may have very different consequences in terms of business models and market structure, depending on how it actually evolves.
[73] See AIT (2021).

considered in the report by AIT (2021), namely, "Open RAN as a game changer," where *"[the] demand for new 5G services is created by verticals that are served by MNOs, but also new entrants specialised in operating networks*."

Operators must acquire the necessary expertise to meet the specific needs of customers in these verticals. This may be costly, and it means that MNOs may address only a share of all possible use cases, where they can reach the minimum scale necessary to justify the investment in expertise. In such a scenario only the most profitable use cases are to be addressed by the operators.

Open RAN as a technology platform

In the second scenario, Open RAN represents a technological or industry platform. For instance, Gawer and Cusumano (2013) define industry platforms "*as products, services or technologies developed by one or more firms, and which serve as foundations upon which a larger number of firms can build further complementary innovations, in the form of specific products, related services or component technologies*." Operating systems like Windows or Linux, or microprocessors developed by companies like Intel and ARM are classical examples of technological platforms. In this view, Open RAN would represent a (technological) platform upon which specialists could offer complimentary hardware or software network components.

Technological or industry platforms stimulate innovation for complementary products and services. They exhibit network effects: the more complementary products and services are available on the platform, the more valuable it is and therefore, the more attractive it becomes for new complementors.

In the context of Open RAN, the technology develops as a platform where suppliers of hardware and software components, and possibly service providers, are brought together and orchestrated. The Open RAN platform attracts suppliers of innovative hardware and software components and manages the integration between them. It may also allow independent service providers to rely on the platform to offer tailored services to specific user segments or users themselves to create their networks (*network as a cloud service*). In this scenario, the main impact of Open RAN stems from the development of new, innovative components and services by a vibrant ecosystem of third-party players, which allow specific consumer segments or use cases to be addressed. Open RAN has a more disruptive effect on the mobile operators (and potentially other parts of the supply chain) in this scenario than in the first one.

This second scenario raises various questions. The first question is how many Open RAN platforms there could or should be and how this might compare to the number of 'traditional' networks in the pipeline model. Having more platforms implies more competition between them, which may be desirable. On the other hand, each competing platform may host only a small network of hardware and software suppliers and service providers, making it hard to reach the critical mass necessary to achieve network effects and take off. This depends on whether providers of components single-home (join only one platform) or multi-home (join most -- if not all -- of them). For instance, developers writing apps for app stores often write for both Google and Apple's platforms. Similarly, a developer with a good idea for Open RAN may write code that works with both the Ericsson and the Nokia radios (or with any other manufacturers' radios). In this case, the overall level of innovation will rise, but opportunities for differentiation between operators in the downstream market will be limited. Open RAN platforms may thus want to reduce multi-homing in various ways to increase differentiation.

The second question is who manages or 'orchestrates' the Open RAN platform. One view is that traditional vendors, like Ericsson or Nokia, could be well placed to play this role, and may have the intention to do so. Yet, it may raise concerns that are common in platform contexts, such as risks of self-preferencing, if the vendors design the platform's interfaces with the view of favouring their network components. Another view is that mobile operators may act as orchestrators themselves by deploying Open RAN solutions, taking the role of an intermediary between suppliers of components and independent service providers. Other firms may also see opportunities, including those involved in other aspects of 5G such as the large cloud providers who also have experience in operating platform businesses. For instance, Amazon Web Services ("AWS") announced a 'private 5G network in-a-box' claiming to have the "Benefits of Cellular with the convenience of Wi-Fi".[74] AWS Private 5G is a new managed service to help enterprises set up and scale private 5G mobile networks using the license-exempt CBRS band.[75]

Faced with a variety of possible use cases, mobile operators may decide not to address all of them but facilitate the development of tailored solutions by third parties. This would correspond to the model of the 'app-store' for mobile operators. Again, the hybrid model of MNOs, being both the orchestrator of the Open RAN platform and possibly provider of solutions on this platform may raise the same kinds of concerns about self-preferencing and the selective disclosure of APIs or use of data as we have seen arising in relation to other platforms (like Amazon) which combine both 'pipeline' and 'platform' activities.

Our conclusion in this section on the evolution of business models is that the possible move towards a technology platform or other new business model for Open RAN may bring substantial benefits and could allow the full potential of new 5G technology to be realised. However, the outlook is uncertain, and some models may raise concerns like self-preferencing, discrimination in the access to APIs or use of data, and so on, if MNOs or upstream vendors like Nokia or Ericsson were to perform this role. The uncertain nature of these developments means that no action is required at this stage, but

[74] Source: https://d1.awsstatic.com/reInvent/re21-pdp-tier1/private-5g/AWS-Private-5G-Infographic-Final.pdf. As well as: "AWS Private 5G out of the box – an unwelcome surprise for operators?" Retrieved: 2021-12-10. Retrieved from: https://mobileeurope.co.uk/press-wire/16346-aws-private-5g-out-of-the-box-is-an-unwelcome-surprise-for-operators. A 'preview' version of the service is in use in the USA by DISH Network, Koch Global Services (which has 122,000 employees around the global and locations in nearly every US state and 60 countries) and Amazon Fulfillment. "Using the AWS console, customers specify where they want to build a mobile network and the network capacity needed for their devices – then AWS delivers and maintains the required small cell radio units, servers, 5G core and radio access network (RAN) software, and subscriber identity modules (SIM cards). AWS Private 5G automates the set-up and deployment of the network, and scales capacity on demand to support additional devices and increased network traffic. There are no upfront fees or per-device costs with AWS Private 5G, and customers only pay for the network capacity and throughput they request. The idea is to eliminate procurement, integration, and maintenance of hardware and software from multiple third-party vendors. Once the equipment is installed and switched on, AWS Private 5G automatically configures and deploys the mobile network. To connect devices to the private network, customers plug the AWS-supplied SIM cards into their devices."

[75] Establishing private 5G networks is a very different proposition to operating a national 5G public network, but it serves to illustrate the possibilities for entry and new business models which 5G may provide in the future.

policymakers should monitor industry developments and, again, be ready to respond rapidly to complaints about anti-competitive behaviour if they should arise.

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RECOMMENDATIONS

4. RECOMMENDATIONS

The O-RAN Alliance and other industry initiatives have made good progress since 2018 in creating conditions under which new participants in the 5G supply chain can collaborate and make investments in equipment and services, which can interwork together so that new markets can be formed. Our analysis suggests that it is essential that this entry occurs if the 'open organisation' benefits of Open RAN, in terms of lower equipment prices and greater innovation, are to be realised. Without additional entry, the benefits of Open RAN could be significantly diminished, and the traditional closed market approach may even be preferable.

Policy makers can contribute to the success of Open RAN in the following ways:

- Limit any interventions which might introduce significant uncertainty for suppliers or operators about the nature of the market for Open RAN equipment or the options available for firms.

- Avoid interventions which may restrict the diversity of sources of supply for operators, for example by seeking to use restrictions to promote the interests of one group of suppliers over another.

- Ensure that any public testing and R&D activities complement those already being undertaken by the industry rather than substituting them or crowding them out.

- Allow the industry to collaborate in testing and development of new Open RAN technologies and standards, and in their integration and acceptance before commercial deployment.

- Be prepared to intervene effectively and quickly if disputes arise between participants, including in relation to claims that incumbent suppliers may be inhibiting the entry of new suppliers. Policymakers should ensure that there is a specialist body that is well qualified to arbitrate and resolve matters quickly to remove uncertainty for investors.

- Support collaboration amongst small MNOs for joint procurement of Open RAN and joint testing to allow them to achieve the minimum efficient scale in system integration; and

- Ensure that the market does not inhibit the emergence of fundamentally new business models, such as platform models, that may better exploit the full potential of Open RAN and 5G technologies, whilst also being mindful that these new business models could themselves give rise to concerns about anti-competitive conduct which may need to be addressed by regulatory bodies.

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GLOSSARY

5. GLOSSARY

1G:	First Generation mobile communications (analogue, circuit switched; telephony)
2G:	Second Generation mobile communications (digital, circuit switched; telephony, short message service; later with GRPS basis internet access)
3G:	Third Generation mobile communications (digital, circuit and packet switching; telephony and internet access)
3GPP:	3G Partnership Project. The 3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organisations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as "Organisational Partners" and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies. The partnership emerged from the regional standardisation activities of 2G. For Europe ETSI is SDO partner.
4G:	Fourth Generation mobile communications (digital, packet switching; internet access)
5G:	Fifth Generation mobile communications (digital, packet switching, virtualised, internet access)
AI:	Artificial Intelligence
API:	Application Programming Interface
ARIB:	Association of Radio Industries and Businesses, Japan
ATIS:	Alliance for Telecommunications Industry Solutions, USA
BBU:	Baseband Unit, a RAN component containing a baseband processing unit. A BBU is connected to a Radio Unit (typically via either fiber optic or RF cabling) and to the Core Network
BSS:	Business Support Systems
CCSA:	China Communications Standards Association
CI/CD:	Continuous Integration / Continuous Delivery
CN:	Core network, together with the RAN it constitutes a mobile network
CNF:	Cloud-native Network Function
CPRI:	Common Protocol for Radio Interface
CU:	Centralised Unit, together with the DU it constitutes the functionality of the Base Band Unit in a disaggregated architecture
DU:	Distributed Unit, together with the CU it constitutes the functionality of the Base Band Unit in a disaggregated architecture
eCPRI:	enhanced CPRI
ETSI:	European Telecommunications Standards Institute
GPU:	General Processing Unit
GSM:	Originally: Groupe Special Mobile; Later: Global System for Mobile communication
GSMA:	GSM Association
H/W:	Hardware
IMT:	International Mobile Telecommunication

IoT:	Internet of Things
IP:	Internet Protocol
ITS:	Institute for Telecommunications Sciences, in the USA
ITU:	International Telecommunications Union, an entity under the hospices of the United Nations
LCM:	Life Cycle Management
LTE:	Long Term Evolution, denotes 4G
MAC:	Medium Access Control
MEC:	Mobile Edge Computing, currently known as Multi-access Edge Computing
MIMO:	Multiple Input Multiple Output, as used in a radio connection
ML:	Machine Learning
MNO:	Mobile Network Operator
MVNO:	Mobile Virtual Network Operator
MVP:	Minimum Viable Product
NFV:	Network Function Virtualisation
NGMN:	Next Generation Mobile Network Alliance
NIS:	Network and Information Systems
NMT450:	Nordic Mobile Telephone System operating at the 450 MHz band
NR:	New Radio, as in 5G NR
NSA:	Non-Stand Alone, as in 5G NSA
NSaaS:	Network Slice as a Service
NTIA:	National Telecommunications and Information Administration, USA
O-CU:	CU according to O-RAN Alliance specification
O-DU:	DU according to O-RAN Alliance specification
O-RAN:	RAN according to O-RAN Alliance specification
OPNFV:	Open Platform for Network Functions Virtualisation
O-RU:	RU according to O-RAN Alliance specification
OSC:	Open-Source Community
OTIC:	Open Test and Integration Center, as related to O-RAN Alliance activities
OTT:	Over The Top, applications
PDCP:	Packet Data Convergence Protocol
PHY:	Physical layer
PoP:	Point of Presence
QoE:	Quality of Experience
QoS:	Quality of Service
OSS:	Operations Support Systems
R15:	Release number 15, of 3GPP specifications
RAN:	Radio Access Network
RF:	Radio Frequency
RIC:	RAN Intelligent Controller
RLC:	Radio Link Control

RRC:	Radio Resource Control
RU:	Radio Unit
SA:	Stand Alone, as in 5G SA
SCF:	Small Cell Forum
SDAP:	Service Data Adaption Protocol
SDO:	Standards Development Organisation
SDN:	Software Defined Network
SDR:	Software Defined Radio
SFG:	Security Focus Group, as part of the O-RAN Alliance activities
SLA:	Service Level Agreement
SMO:	Service Management and Orchestration
TIFG:	Test and Integration Focus Group, within the O-RAN Alliance
TIP:	Telecommunications Infrastructure Project
TSC:	Technical Steering Committee
TSDSI:	Telecommunications Standards Development Society, India
TTA:	Telecommunications Technology Association, Korea
TTC:	Telecommunication Technology Committee, Japan
UE:	User Equipment
UI:	User Interface
vCU:	Virtual CU
vDU:	Virtual DU
VNF:	Virtual Network Functions
vRAN:	Virtual RAN

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ANNEX: OTHER ASPECTS OF THE 5G ARCHITECTURE

6. ANNEX: OTHER ASPECTS OF THE 5G ARCHITECTURE

This Annex discusses other features of 5G which are either incorporated into the Open RAN concept itself and/or which are other features of 5G.

NFV (Network Function Virtualisation)

The motivation to move towards NFV can be summarised as dissatisfaction with the model for deploying new network services. This has led to a large and increasing variety of proprietary hardware appliances and the introduction of a new service requiring yet another variety of equipment, for which finding the space and power to accommodate these boxes was becoming increasingly difficult. This difficulty was compounded by “increasing costs of energy, capital investment, and rarity of skills necessary to design, integrate and operate increasingly complex hardware-based appliances”. Moreover, AT&T, one of the early adopters of NFV in 2013, argued that hardware lifecycles are becoming shorter as technology and service innovation accelerates, hence, the old model would further constrain innovation.

NFV aims to address these problems by evolving towards standard IT virtualisation technology to consolidate many network equipment types onto industry-standard high-volume servers, switches and storage that can be in data centres, network PoPs or on customer premises. This involves the implementation of network functions in software, called Virtual Network Functions (VNFs), that can run on a range of general-purpose hardware, and that can be moved to, or instantiated in, various locations in the network as required, without the need for installation of new equipment. This is intended to lead to lower capital expenditures, benefiting from economies of scale in the IT industry; lower operating costs; faster deployment of new services; energy savings; and improved network efficiency.[76]

5G slicing and open APIs

Another innovative feature of the 5G architecture is the tailoring of services through network slicing. Network slicing makes use of the virtualisation of the 5G system in terms of the flexible allocation of resources through software. 3GPP defines Network Slice as a Service (NSaaS). NSaaS can be offered by an MNO to its client in the form of a communication service. NSaaS also allows the client to use and optionally manage the network slice instance (see Figure 7).

According to the 5G Americas White Paper: “The ‘Network Slice as a Service’ model envisions that vertical industries, mobile virtual network operators (MVNOs), over-the-top (OTT) service providers or mobile network operators (MNOs) must manage aspects of a network slice as if it was a separate, dedicated network. Efficiently enabling and operating such a business requires available Application

[76] Source: AT&T (2013). For a general discussion of virtualisation and Software Defined Networking see: Göransson and Black (2014); Stallings (2016). For a specific discussion in relation to 5G see: Chapter 3 in Osseiran, Monserrat et al. (2016).

Programming Interfaces (API). The need for APIs to support the 'Network Slice as a Service' model also applies to the management framework".[77]

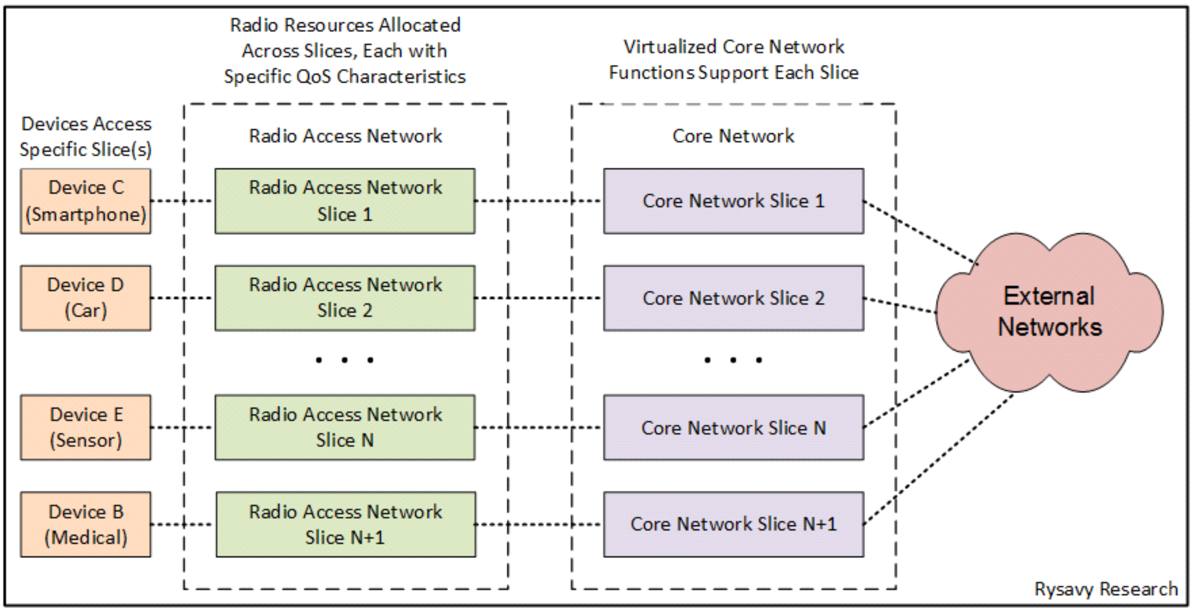

Figure 7. Mobile network slicing. Source: 5G Americas (2019 p47)

Artificial Intelligence/Machine Learning

The complexity of 5G means it requires AI/ML to operationalise it. Ericsson argues: "The introduction of 5G New Radio has made the RAN more complex by increasing the number of band combinations that have to be managed and extending the capability of the network to support multiple network slices with different characteristics. At the same time, the high degree of agility and flexibility that cloud-native RAN implementations demand makes manual intervention virtually impossible. To operate efficiently, a network at this level of complexity requires RAN automation".[78] The application of AI/ML not only covers the RAN, but includes the CN, as well as use case development as illustrated in Figure 8.[79] The O-RAN Alliance points out that with AI/ML, performance management can move from being cell-centric to user equipment-centric.[80]

[77] Source: 5G Americas (2019c).
[78] Source: Corcoran, Westerberg et al. (2021).
[79] For a discussion of AI/ML applied in 5G see for instance: Calabrese, Frank et al. (2019); Corcoran, Westerberg et al. (2021).
[80] Source: O-RAN Alliance (2020).

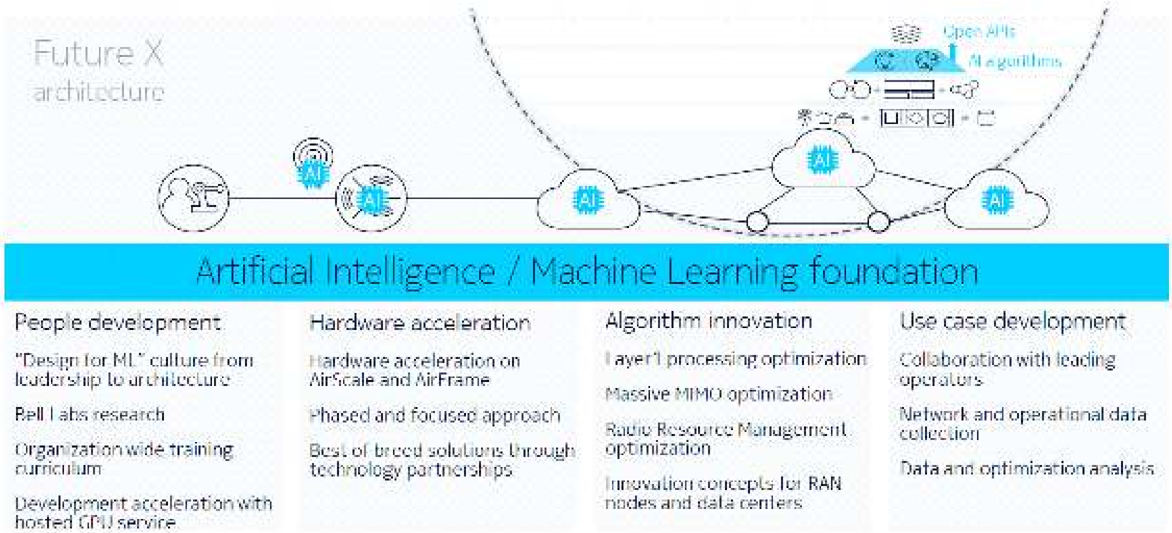

Figure 8. Artificial Intelligence / Machine Learning foundation. Source: Nokia (2018)

Cloudification

As the developments in the cloud space are continuing with the aim to improve performance, one of the approaches selected for 5G is to move away from virtual machines towards a so-called cloud-native approach using containerisation and a 'stateless' microservices architecture.[81] This provides lower operating system overhead, and it provides for greater granularity and thereby efficiency and flexibility in running processing loads. It also supports continuous integration and continuous deployment (CI/CD) of new software and improved life cycle management (LCM).[82] ETSI has updated its architecture towards cloud native and these new concepts are now being integrated into the standardisation process by 3GPP.[83] The cloud native architecture of 5G is depicted in Figure 9.

[81] To be properly classified as cloud native, microservices need to be 'stateless', which means there is a separation of processing from the associated data and the storage of the data in the cloud. Another attribute is 'dynamic orchestration', the actively scheduling and optimising of resource utilisation while providing observability, resiliency, and an immutable infrastructure, typically enabled by the container orchestrator "Kubernetes". 5G Americas (2019) see also: https://www.oracle.com/a/ocom/docs/industries/communications/cloud-native-journey-telecomm-wp.pdf

[82] Sources: 5G Americas (2019) Ericsson: "Building a cloud native 5G Core: the guide series" at: https://www.ericsson.com/en/blog/2020/10/building-a-cloud-native-5g-core-the-guide-series; Nokia: "Going cloud native": https://www.nokia.com/networks/cloud-native/?did=d000000006je&gclid=EAIaIQobChMI0-PhyIqn9QIVTuTICh1tKwmrEAAYAyAAEgK3gPD_BwE

[83] Source: https://www.etsi.org/newsroom/press-releases/1849-2020-11-etsi-unveils-first-cloud-native-vnf-management-specifications

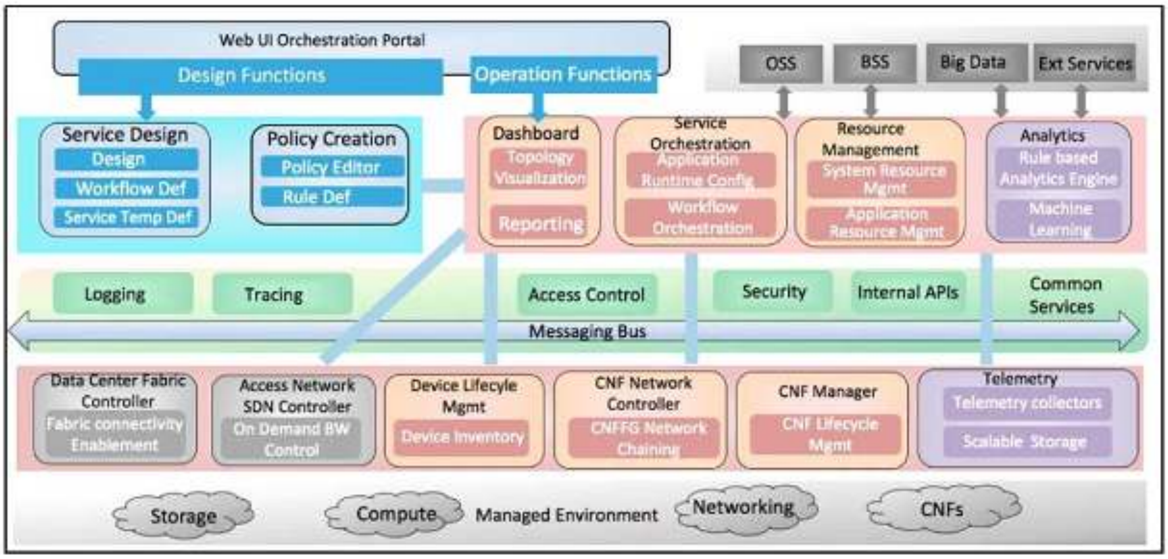

Figure 9. A pragmatic NFV software architecture in the Cloud Native environment. Source: 5G Americas (2019 p37)

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