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# Impacts of Open Radio Access Networks for Operators, Policymakers, and Consumers

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# Executive Summary

In April 2023, the National Security Council (NSC) issued its principles for 6G, including that 6G networks should be "open and resilient by design."

This statement, along with the conclusion of initial 5G network rollouts in advanced wireless markets, was a catalyst for research conducted for this paper from spring 2023 to November 2024, with the goal of understanding how Open Radio Access Networks, or Open RAN, will fit into this new communications landscape. Open RAN seeks to promote greater hardware and software interoperability between different elements in RAN, which marks a change from previous generations, which were generally provided by one supplier. This research was thus focused on addressing the following questions:

- What is the significance of Open RAN for network operators that are making 5G supplier decisions, or that are beginning to plan for 6G?
- What is the current state of supply in the RAN? Who are significant suppliers?
- What actions can policymakers take to facilitate supplier diversity in the RAN? What would be the consequences of lack of action, or sporadic action?

Key points from the report are summarized below:

- Radio access network (RAN) equipment refers to equipment in a wireless telecommunications system that provides the wireless access link with the customer handset (e.g., smartphones), and also manages radio resources.
- The relationship between network operators and network equipment suppliers is one of co-specialization. Value is jointly created, and one does not exist without the other.
- The network equipment market, and the RAN market in particular, is concentrated on a few key suppliers. The top five RAN suppliers — Huawei, Ericsson, Nokia, ZTE and Samsung — have about 95% revenue share. The top three suppliers — Huawei, Ericsson and Nokia — have around 75% share. This concentration, combined with the relationship of co-dependence between operators and suppliers, means that network operators worldwide are dependent on the ability of a few key suppliers to continue to innovate.
- For example, as of 2010, Nokia and Huawei's R&D expenditures were roughly equivalent. As of today, the individual R&D budgets of Huawei and Samsung are each greater than those of Nokia and Ericsson combined. Huawei, a more diversified company than Nokia and Ericsson, spends 23% of revenue on R&D; Nokia and Ericsson each spend around

17% of revenue on R&D. Were any key suppliers to struggle, be disrupted, or fail to continue to innovate, the broader industry would suffer.

- The high levels of concentration in the RAN supplier market led network operators in multiple regions around the world to investigate Open RAN as a means of nurturing alternatives to current suppliers.
- Open RAN refers to a movement to unbundle the RAN, i.e., to: (1) disaggregate what historically had been monolithically provided by one supplier; (2) facilitate greater interoperability between supplier hardware and software; and (3) create greater supplier diversity in the RAN market.
- Open RAN also means standardizing and publishing the interfaces between different elements in the RAN on a more rigorous basis than had been traditionally done by standards bodies such as 3GPP. Different organizations developed for this purpose have largely consolidated their work into the O-RAN Alliance. The Telecom Infra Project (TIP) is another forum for this work.
- Both Huawei and ZTE have been subject to restrictions in the United States and various allied nations. In the near term, this has narrowed the set of choices available to network operators. These restrictions have also provided opportunity for longstanding RAN suppliers, such as Samsung, NEC, and Fujitsu, to gain additional global market share.
- Open RAN has enabled some new greenfield network operators, such as Rakuten Mobile, to enter the market on a relatively capital-efficient basis. Incumbent network operators have embraced different forms of Open RAN, such as multi-vendor RAN, or "Open RAN-ready" single-vendor RAN.
- While the potential for lower equipment costs is part of the attraction of Open RAN, network equipment procurement costs represent only a small percentage of the total cost of ownership over a 10-year lifespan.
- If the RAN is unbundled, an integrator is required to stitch the unbundled network elements back together. This integrator can be the network operator itself; a network equipment supplier; or a third party, such as an IT services provider.
- By (1) standardizing and publishing more network interfaces than 3GPP traditionally had and (2) by putting some elements of the RAN into the cloud, Open RAN (and, to an extent, Cloud RAN or virtualized RAN) creates new vectors for security risk compared to traditional RAN. In particular, use of an O-Cloud represents a vector of risk unique to Open RAN deployments. However, publishing and standardizing interfaces also has the benefit of reducing supply chain risk and supplier lock-in in the event that access to a key supplier is interrupted.
- Recent reporting on cyber intrusions into multiple US telecommunications networks (e.g., Salt Typhoon) highlights (a) vulnerabilities from interconnectedness (e.g., vul-

nerabilities in one network can lead to other networks that interconnect with it being compromised) and (b) the importance of network modernization. Reporting indicates hackers may have exploited interfaces used for lawful intercept to gain access to traffic and call detail records (CDRs) from persons of interest. This highlights the need to modernize network operators (e.g. move to 5G Standalone) and ensure law enforcement equipment and operational practices are modernized.[1]

Based on the research findings, this report makes the following recommendations:

*Recommendations to Network Operators:*

- Some network operators interviewed for this report commented that they want to see Open RAN suppliers reach "feature parity" with traditional suppliers. Network operators should thoughtfully assess just how important support of legacy features from the 2G or 3G era will be in a 5G/6G era. For how long, and for what purpose, would new 5G/6G RAN suppliers be expected to provide 2G/3G-era features? Recent cyber intrusions into US telecom networks — which may have exploited interfaces provided for lawful intercept — highlight the urgency to modernize US communications networks.[2] Network operators should be looking forward, and investing in network modernization, rather than forcing new suppliers to invest in support of legacy features.
- Operators should re-invest in their network integration capabilities, to enable more robust services and to mitigate dependency on a concentrated set of suppliers. Open RAN enables creative combinations of different RAN suppliers.
- Network operators will often issue debt for the purpose of network investments or spectrum purchases. To foster greater liquidity in the smaller network operator market, we recommend exploring establishment of a "Telly Mac" that would facilitate bundling of compliant network operator debt issuances, similar to how Fannie Mae and Freddie Mac help provide liquidity to the mortgage market.

*Recommendations to the National Telecommunications and Information Administration (NTIA):*

- We recommend that the NTIA continue on the path set with its 2023 5G Challenge, and begin planning for a series of 6G challenges, with a focus on open, resilient networks provided by non-traditional suppliers.

1 Dozens of countries hit in Chinese telecom hacking campaign, top US official says, Wall Street Journal, December 4, 2024. https://www.wsj.com/politics/national-security/dozens-of-countries-hit-in-chinese-telecom-hacking-campaign-top-u-s-official-says-2a3a5cca

2 T-Mobile USA was one the network operators impacted.On November 27 2024, T-Mobile's Chief Security Officer issued a statement (An update on recent cyberattacks targeting US wireless companies) describing T-Mobile's multi-layered security practices, and citing the benefits of having migrated to 5G Standalone. A benefit of this, as described in our 2020 report on Security Implications of 5G, is improvements in authentication between handset and base station. https://www.t-mobile.com/news/un-carrier/update-cyberattacks-targeting-us-wireless-companies

- We recommend that the NTIA consistently issue SBIR (Small Business Innovation Research) solicitations for Open RAN to help nurture small business and startup suppliers.
- We recommend that the Public Supply Chain Wireless Innovation Fund be renewed after it is depleted, as it will take multiple iterations to meaningfully impact the state of RAN supply. Consistency of funding opportunities will help nurture suppliers, and also induce more innovators to direct resources towards solving the technical challenges involved in developing open, resilient networks.

*Recommendations to the Federal Communications Commission (FCC):*

- The FCC should measure the state of RAN and telecom equipment supply as part of its broadband measurement process. Increased clarity on the state of supply would help in understanding dependencies and potential vulnerabilities.
- We recommend fully funding the FCC rip-and-replace fund, which is underfunded relative to industry requests by at least $3 billion. Upgrades should be done with the broader goal (see P2) of network modernization and making networks more open and resilient.
- The FCC's $9B Rural 5G Fund remains unallocated. These funds should be put to work with the service goal of providing better 5G coverage in rural areas, and with the policy goal of enabling more modern, open and resilient networks, not just in urban areas, but also rural areas.
- We also recommend that the FCC seek to better coordinate its funding opportunities with NTIA.

In addition, we recommend that the US government, potentially together with allied governments, contemplate an "Operation Warp Speed" for wireless, i.e., a focused effort to drive rapid innovation (in the US case, for 6G) similar to the effort that led to the accelerated development of the COVID vaccine. If governments truly want open, resilient wireless networks for 5G or 6G, more concentrated guidance and support could help deliver this outcome. Further, allied nations, such as members of the Quad (Australia, India, Japan, and the United States), could pool their resources to provide further scale for such an initiative.

# Foreword

In September 2020, I published *Security Implications of 5G Networks*, also with the support of the Center for Long-Term Cybersecurity at UC Berkeley.[3] That paper looked at both security risks and benefits associated with 5G networks. Most network operators are running multiple generations of network equipment (e.g., 3G, 4G, 5G) in parallel. For that reason, network operators typically first rolled out 5G RAN (Radio Access Network equipment, e.g., antennas) paired with existing 4G Core equipment.[4] For that reason, we assessed that many of the salient defining features of 5G, and also security benefits, would have to wait until 5G Core was also implemented. That in turn would likely have to wait until 5G handsets got to critical mass, i.e., when over 50% of customer handsets were 5G-compatible.

I started work on this follow-up paper in spring 2023. There were multiple catalysts for starting research:

- 5G handset penetration in the US market had passed 50%. This would mean that 5G network operators would likely also implement 5G Core, and start looking ahead to 6G. Worldwide, 5G penetration was approaching 20%.
- In April 2023, the National Security Council (NSC) issued its principles for 6G, including that 6G networks should be "open and resilient by design."
- In May 2023, the National Telecommunications and Information Agency (NTIA) published an Open RAN Security Report, in advance of a meeting between the members of the Quadrilateral Security Dialogue (Quad), composed of Australia, India, Japan, and the United States.
- The US government in particular has taken a host of actions in recent years both to promote broadband access and also to increase RAN supplier diversity, such as through funding opportunities in the CHIPS and Science Act of 2022.

In aggregate, these developments indicated that a robust assessment of Open RAN was timely— for network operators, for policymakers, and for network equipment suppliers themselves. With these stakeholders in mind, this paper seeks to address the following questions:

3 Metzler, Security Implications of 5G Networks, September 2020 https://cltc.berkeley.edu/publication/cltc-report-security-implications-of-5g-networks/

4 For details on Standalone 5G versus Non-Standalone 5G implementation, see Figure 14, GSMA 5G Implementation Guidelines, July 2019. https://www.gsma.com/solutions-and-impact/technologies/networks/wp-content/uploads/2019/03/5G-Implementation-Guideline-v2.0-July-2019.pdf

- What is the significance of Open RAN for network operators that are making 5G supplier decisions, or that are beginning planning for 6G?
- What is the current state of supply in the RAN? What actions can policymakers take to facilitate supplier diversity in the RAN? What would be the consequences of lack of action, or sporadic action?
- At a higher level, what is the significance and benefit of innovation in the RAN?

# Methodology

I began work on this research in April 2023, timed with the RSA Security Conference held each year in San Francisco. Since then, I have interviewed a range of network operators, network equipment suppliers, analysts, and policymakers. With regards to Open RAN deployments, I have spoken with both greenfield network operators and mobile network operators who are assessing or deploying Open RAN equipment in the context of existing network deployments. For industry data, I have utilized industry data from analysts Dell'Oro and Omdia, in addition to data from industry groups such as GSMA and CTIA, and investor relations material from network operators and network equipment suppliers.

# Why Innovation in the RAN Matters

## NETWORK INNOVATION SUPPORTS A MORE CONNECTED, BETTER INFORMED SOCIETY

Mobile phones are our first connection point for real-time information in our personal and professional lives. Smartphone users may check their phones over 100 times per day.[5] Further, for "smartphone-dependent" households, i.e., those for whom mobile connections are the only means of accessing the internet, mobile connectivity is a lifeline to the rest of the world.[6] A well-connected populace can better participate across all the spheres of society.

Arthur C. Clarke famously wrote that "any sufficiently advanced technology is indistinguishable from magic." In this author's view, mobile networks embody this: we are wirelessly and seamlessly connected across much of the globe, to the point that we only notice the absence of connectivity, rather than the daily miracle of keeping billions of people connected in real time.

Governments and civil society have a stake in the health, reliable operation, and security of the mobile networks that support this pervasive, real-time connectivity. A vibrant, innovative mobile industry, including mobile network infrastructure, provides a multiplier not just to consumer and enterprise customers, but also to civic and governmental stakeholders. Further, a society that aspires to digitally transform — for example, through digitization of civic services — needs healthy, reliable mobile network operators as a starting point. In sum, over 50 years after the first cellular call, innovation in the RAN still matters.

## THE MOBILE INDUSTRY TODAY

Over 50 years have passed since Motorola executive Martin Cooper placed the first mobile call on the streets of Manhattan in 1973, using a handheld, battery-powered Motorola DynaTac. The

5 Americans check their phones 144 times per day; here's how to cut back; Fortune, July 2023. https://fortune.com/well/2023/07/19/how-to-cut-back-screen-time/

6 CTIA, the US wireless carrier association, estimates that 15% of broadband households in the United States are smartphone-only, and that 71% of households do not have a landline telephone.

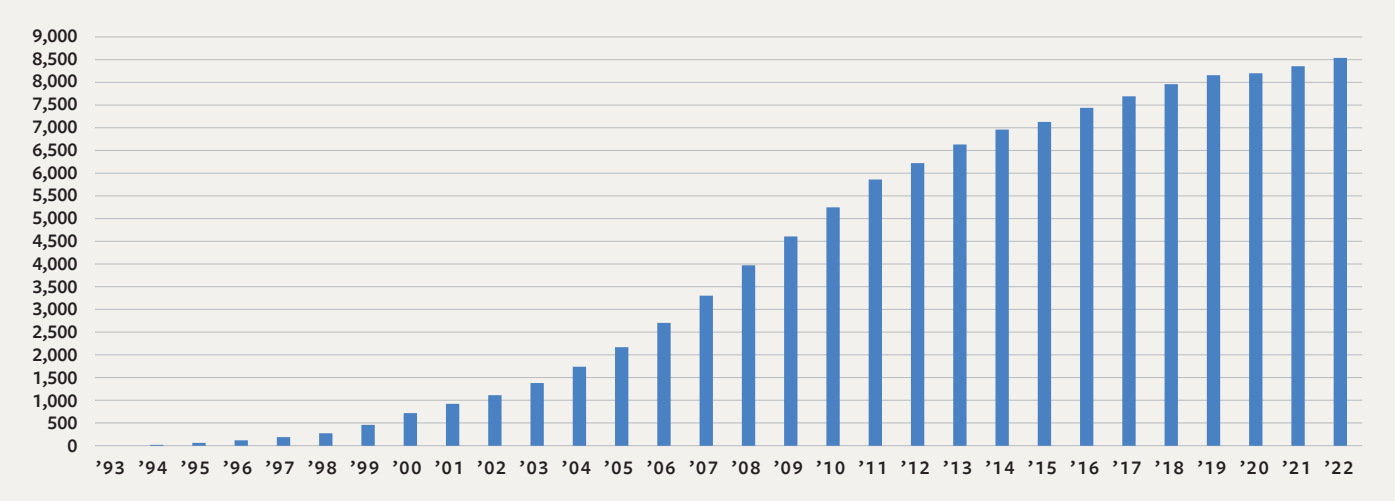


**Figure 1: Number of global mobile lines, 1993–2022, in millions. ITU data, February 2023.**

origins of mobile telephone date back further, to 1946, when AT&T first demonstrated a mobile telephony service targeting in-car users. Thus, it was symbolic that the call Cooper proudly placed in April 1973 was to Joel Engel, then head of research at AT&T Bell Labs.

Since then, the mobile industry has blossomed worldwide. As of the end of 2023, the Global System for Mobile Communications Association (GSMA) estimated there were 5.6 billion unique mobile subscribers in the world using 8.6 billion SIM connections, with an additional 3.5 billion connected devices (IoT connections) supported by cellular lines.[7] GSMA further estimates that mobile technologies and services contributed 5.4% of global GDP, or $5.7 trillion, of which $1.55 trillion came directly through the mobile ecosystem of network operators, infrastructure and equipment, and content and services.[8]

The rate of global subscriber growth has slowed in recent years, but total subscriber lines still increase by 150 to 200 million annually. GSMA estimated there were 111 mobile subscriptions per 100 people worldwide as of 2023.[9] Looking ahead, GSMA estimates there will be 6.3 billion unique mobile subscribers by 2030, or about 73% of a projected global population of 8.6 billion.[10]

7 GSMA, The Mobile Economy — 2024. https://www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-economy/wp-content/uploads/2024/02/260224-The-Mobile-Economy-2024.pdf SIM: Subscriber Identity Module

8 GSMA, The Mobile Economy 2024.

9 International Telecommunications Union (ITU), fixed and mobile subscriptions. Accessed July 2024. https://datahub.itu.int/dashboards/?id=2

10 United Nations, World Population Prospects, 2017 revision, announced June 2017. https://www.un.org/en/development/desa/population/events/pdf/other/21/21June_FINAL%20PRESS%20RELEASE_WPP17.pdf

Both handsets and mobile infrastructure require access to power, and thus our ability to connect more than two billion additional subscribers is influenced not just by service availability and affordability, but also the availability of power sources.[11]

With the broad adoption of smartphones, data traffic on mobile networks has increased dramatically. Further growth in data traffic per connection per month is predicted. GSMA's regional estimates of growth in per-connection traffic from 2023 to 2030 are provided below.

| | 2023 | 2030 | CAGR 2023–2030 |
|---|---|---|---|
| Asia-Pacific* | 14 | 53 | 21% |
| Eurasia | 13 | 41 | 18% |
| Europe | 17 | 71 | 22% |
| Greater China | 13 | 54 | 23% |
| Latin America | 7 | 32 | 23% |
| MENA | 10 | 31 | 18% |
| North America | 29 | 90 | 17% |
| Sub-Saharan Africa | 2 | 9 | 23% |

**Figure 2: Monthly data usage per line per month, by region, in gigabytes, along with compound annual growth rate (CAGR).*Asia-Pacific does not include Greater China.**[12]

## NETWORK TECHNOLOGY UPGRADES

GSMA predicts that 56% of global connections in 2030 will be 5G connections, and that 90% of subscriber lines in North America will be 5G.[13] Network operators generally upgrade network technologies (generations, e.g., 1G, 2G, 3G, etc.) on a once-per-decade cadence, with incremental mid-generation upgrades (e.g., 2.75G, 3.5G) occurring in between. Generations and representative services are introduced below.

- 1G: The Motorola DynaTac used by Marty Cooper to call AT&T in 1973 was later sold as a 1G (first-generation) phone in the 1980s. 1G supported analog voice service. There were multiple 1G systems, such as AMPS in the United States, NMT in parts of Europe, and TACS in the United Kingdom. 1G voice systems were unencrypted.

11 In 2007, the author helped write the business plan for a wireless infrastructure startup focusing on network operators in rural areas in emerging economies. Grid availability, labor, and energy costs were a factor in estimating minimum viable service prices for network operators.

12 GSMA, The Mobile Economy 2024.

13 Ibid.

- 2G: The first 2G service, GSM, was launched in Finland in 1991. 2G added encryption to calling. In addition to voice, 2G phones supported texting, and later added lightweight data services. There were multiple 2G standards: GSM, in Europe; TDMA and CDMA, in the United States; and PDC, in Japan. The first iPhone, launched in 2007, was a 2.75G or EDGE phone.
- 3G: NTT DOCOMO launched 3G service in Japan in 2001. 3G enabled mobile web services and also early smartphones, such as RIM's BlackBerry. The second iPhone, launched in 2008, was the first 3G iPhone. Mid-generation 3G enhancements, such as HSPA (3.5G), enabled more robust data services.
- 4G: TeliaSonera launched the first 4G service in Norway in 2009. Verizon launched 4G in the United States in 2010. 4G networks, combined with the advent of mobile OS platforms and current-generation smartphones, enabled today's mobile app economy.
- 5G: KT launched service in Korea timed with the 2018 Winter Olympics. In the US, initial 5G service began in 2019. 5G networks lowered latency, or network response time, enabling a more diverse set of applications, such as enterprise and industrial applications.
- 6G: By 2030, it is likely that operators in advanced wireless markets will have launched 6G service. A variety of governments, including China, Finland, India, Japan, South Korea, and the United States, have issued announcements indicating their intent to take leadership roles in 6G standards development and network deployments.

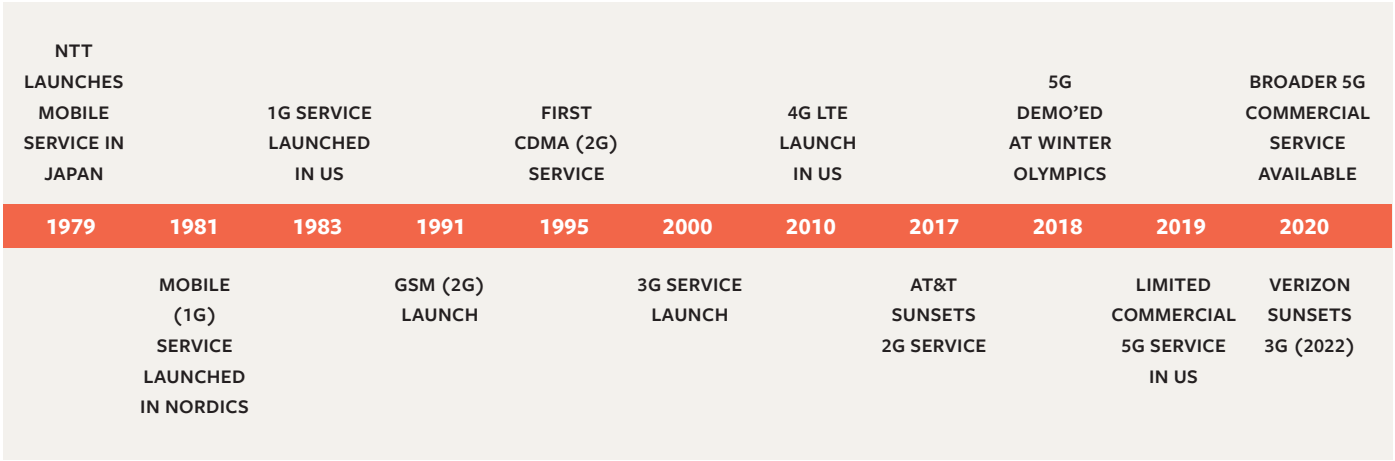


**Figure 3: Network generation launch milestones. Author diagram.**

# Mobile network operators and their suppliers

American Bell Telephone, the antecedent to American Telephone & Telegraph Co. (AT&T), acquired its supplier Western Electric in 1882, making Western Electric the sole supplier of Bell telephones and telephone equipment. This continued for decades, until the Carterfone decision of 1968, which enabled third parties to develop equipment to attach to AT&T's network.[14,15,16]

In the modern era, mobile network operators, including those derived from the former Bell System (AT&T and Verizon), are generally integrators of products and services provided by established outside suppliers.[17] Key suppliers include handset partners like Apple and Samsung, and network equipment partners, such as Ericsson, Nokia, and Huawei. While there is local market variance, especially with regards to handsets, major handset and network suppliers are used worldwide. In particular, a largely consistent set of network equipment suppliers is used across the globe. (When teaching, I often refer to telecom as a global industry with local deltas, whether handsets or services.)

This has benefits to network operators: for example, operators currently deploying 5G networks can leverage the expertise that suppliers have accumulated over the course of rolling out networks elsewhere in the world. For example, Ericsson, a network equipment supplier headquartered in Stockholm, Sweden, claims to have customers in more than 180 countries.[18] Meanwhile, the company's network operator customers focus on customer acquisition and retention, network operation, and development and delivery of new services. Network operators are also responsible for acquisition of the wireless spectrum used to provide service, typically on an auction or an awarded basis.

14 https://meridian.allenpress.com/american-archivist/article/29/1/55/22412/The-Western-Electric-Historical-Library

15 When AT&T was broken up in 1984, Western Electric and Bell Labs were included in AT&T Technologies, which later was spun out as Lucent Technologies in 1996.

16 https://historyofcomputercommunications.info/section/3.10/Carterfone,-Computer-Inquiry-I-and-Deregulation-1967-1968/

17 In 2008, the author heard Dan Hesse, formerly with AT&T and then CEO of Sprint, paraphrase the BASF tagline in describing the role of the network operator: "we don't make the paint, we make it brighter."

18 For more, see Ericsson 2023 annual report. https://www.ericsson.com/4933e7/assets/local/investors/documents/2023/annual-report-2023-en.pdf

The relationship between network operators and network equipment suppliers is one of co-specialization. Value is jointly created, and one does not exist without the other.[19] Similar examples are seen in other mature industries, such as the automotive industry or the passenger air travel industry. While this co-specialization has enabled consistent service and sharing of best practices around the globe, the consolidation of the network equipment market, and the RAN market in particular, means that network operators worldwide are dependent on the ability of a few key suppliers to continue to innovate. Indeed, the persistent struggles of Boeing, a key supplier of passenger airplanes along with Airbus, should be seen as a cautionary tale for other industries with similar patterns of co-specialization. If a key supplier struggles, the broader industry suffers.

There are many well-known examples of co-specialization, particularly in technology markets. Recent examples include Apple and Foxconn, Apple's main manufacturing partner; NVIDIA and TSMC, NVIDIA's main fabrication partner; or Tesla and its battery suppliers, such as Panasonic and LG Chemical. As dramatic as NVIDIA's recent success has been, reporting indicates that NVIDIA customers may have delivery lead times as long as a year, and that TSMC's 3nm fabrication capacity is fully booked until 2026. This illustrates both the benefits and tradeoffs of co-specialization for a fabless semiconductor company working with a fabrication partner on a largely single-source basis.[20]

Strategist Pankaj Ghemawat, in his classic article *Sustaining Superior Performance*,[21] highlights four forms of risk to sustaining corporate performance: imitation, substitution, holdup, and slack. *Imitation* refers to competition by alternate providers using largely the same assets and capabilities (e.g., lower-cost alternatives); *substitution* refers to some alternate form of fulfilling the same customer need (e.g., substitution from netbooks to tablets, or from PC to mobile); *slack* refers to underperformance relative to the company's capabilities, due perhaps to bureaucracy or coordination costs (i.e., diseconomies of scope or scale); and *holdup* refers to value appropriated by co-specialization partners.

19 Cospecialization is common in technology markets, from handsets to networks to automotive. It can be essential to value creation — essentially two firms share their comparative advantages — but it can also mean both firms can be susceptible to being held up by the other. If a network equipment supplier underperforms, network operators suffer, and vice-versa. The author suggests Pankaj Ghemawat's *Strategy and the Business Landscape* for a fuller exploration.

20 Toms Hardware, February 2024: Wait times for NVIDIA's AI GPUs ease to three to four months https://www.tomshardware.com/tech-industry/artificial-intelligence/wait-times-for-nvidias-ai-gpus-eases-to-three-to-four-months-suggesting-peak-in-near-term-growth-the-wait-list-for-an-h100-was-previously-eleven-months-ubs

21 HBR, 1997; also in Ghemawat's strategy textbook *Strategy and the Business Landscape*, now on its fifth edition.

Boeing's struggles are an example of supplier holdup. The combination of operational lock-in (e.g., staff training, or gate or jetway alignment), multi-year delivery lead times from Airbus, and the availability of earlier (albeit less fuel-efficient) generations of 737 have meant that Boeing's 737-9 customers have largely stayed with Boeing. Similarly, lock-in between cellular network operators and their supplier partners is high, a topic we will explore further in this paper as we look at how some network operators have opted for "single vendor Open RAN" from an established supplier such as Ericsson, rather than multi-vendor Open RAN.[22, 23]

22 Light Reading, February 2024, Single vendor Open RAN is spreading like a virus. https://www.lightreading.com/open-ran/single-vendor-open-ran-is-spreading-like-a-virus

23 NEC blog post, March 2023: Is a single vendor Open RAN solution really open? https://www.nec.com/en/global/solutions/5g/Blog-Speaking-Openly-About-Open-Networks-Is-a-single-vendor-Open-RAN-solution-really-open.html

# The RAN market, telecom equipment market, and network operator capital expenditures

Radio access network (RAN) equipment refers to equipment in a wireless telecommunications system that provides the wireless access link with the customer handset (e.g., smartphones, sometimes known as user equipment or UE), and also manages radio resources. Product examples include antennas, remote radio heads, baseband units, fronthaul and backhaul transport products,[24] and related software and silicon products. These are shown in a 5G configuration in Figure 4, a diagram from Nokia Networks.

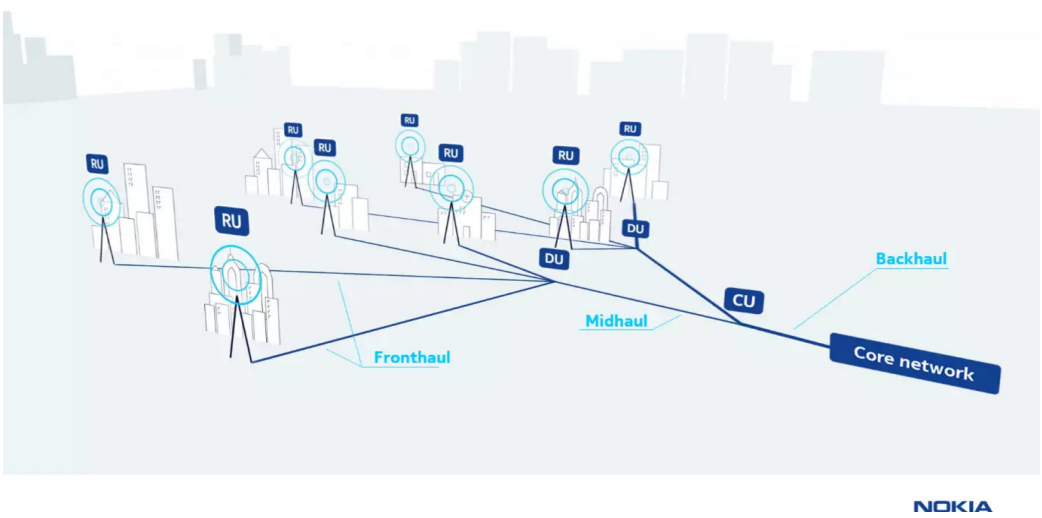


**Figure 4: 5G RAN deployment configuration. Nokia Networks, 2020. RU: radio unit; DU: distributed unit; CU: control unit.**[25]

Traffic from the mobile wireless network is relayed back to a core wired network. Depending on the network operator, the RAN equipment provider may be involved in operation and support of its own equipment within the operator network.

24 Fronthaul refers to connections between remote cell sites (RRH in 4G, RU in 5G) and baseband products (BBU in 4G networks, DU in 5G networks); backhaul refers to networks relaying traffic from the CU to a core wired network.

25 A DU may support multiple RU. CU are typically regional. A DU can sit "on site" (near a cell tower) or in an operator area data center, depending on the distance and fiber availability in the area. DU can be up to 20km from the RU, though some operators (in highly fiber-dense countries) claim that distances of up to 50 km are possible. CU are typically centralized to save on TCO. Source: operator interviews.

While makers of RAN equipment conceivably have the capabilities to stand up wireless carriers themselves (and may indeed manage networks on behalf of their customers), they are largely B2B companies. Exceptions are the handset business units that some RAN suppliers retain, such as Samsung and Huawei. These engage in direct consumer marketing, if not service provision and billing. Network equipment suppliers that also have handset businesses may choose to bundle handsets with network equipment when contracting with network operators.

The Wireless Infrastructure Association (WIA) estimates that there are 142,000 cell towers and 209,470 macrocells in the United States.[26] One tower, particularly any of those operated by specialist third-party tower operators like American Tower Corporation or Crown Castle Inc., may host equipment from multiple operators in a host-tenant model. The WIA further estimates there are an additional 747,400 indoor small cells and 452,000 outdoor small cells in the US.[27] In its 2022 member survey, CTIA, the US wireless carrier association, estimated that there were 419,000 operational cell sites in the US.[28] In comparison, data from China's Ministry of Industry and Information Technology (MIIT) indicates that, as of February 2024, there were 3.5 million 5G base stations in China, and close to 12 million base stations in total in China when including all network technology generations.[29, 30]

GSMA estimates that global mobile network operators will spend $1.5 trillion in capital expenditures between 2023–2030, or close to $190 billion annually. In the United States, CTIA, in its 2023 member survey, estimated that network operators invested $39 billion in their networks in 2022, up from $35 billion in 2021.[31] As a rule of thumb, roughly one-third of network operators' capital expenditures go toward access equipment.[32] Other expenditures include civil costs (construction), transport equipment, cloud infrastructure, IT, and software.[33]

26 WIA defines a tower as a structure over 50 feet high. A macrocell refers to a cell site designed for wide-area coverage, such as those on hilltops or along highways. Operators will typically deploy macrocells for wide-area coverage, using lower frequency spectrum that propagates further, and small cells (microcells) for capacity in defined areas, using higher-frequency spectrum with more limited propagation.

27 Wireless Infrastructure Association: 2022 Key Industry Statistics; published Q1 2023.

28 CTIA operator member survey, 2022. https://api.ctia.org/wp-content/uploads/2022/09/2022-Annual-Survey.pdf

29 RCR Wireless, April 2024: China ends February with over 3 million 5G base stations. https://www.rcrwireless.com/20240409/5g/china-ends-february-over-3-million-5g-base-stations

30 China's Ministry of Industry and Information Technology (MIIT), via Statista. Accessed July 2024.

31 CTIA 2023 member survey. https://www.ctia.org/news/2023-annual-survey-highlights

32 Dell'Oro, April 2023: Worldwide telecom capex to decline in 2023. https://www.delloro.com/news/worldwide-telecom-capex-to-decline-in-2023/

33 Omdia, February 2023: Introduction to the global telecoms index tracker. https://omdia.tech.informa.com/om029652/introduction-to-the-global-telecoms-capex-tracker

As of 2022, Dell'Oro estimated the global telecom equipment market at $100 billion, with the RAN segment at about $41B.[34] Industry revenue share estimates for 2022 and 2023 are provided in Figure 5.[35]

| | 2022 | 2023 |
|---|---|---|
| Huawei | 28% | 30% |
| Nokia | 15% | 15% |
| Ericsson | 14% | 13% |
| ZTE | 11% | 11% |
| Cisco | 5% | 6% |
| Ciena | 3% | 4% |
| Samsung | 3% | 2% |
| Others | 20% | 20% |

**Figure 5: Telecom equipment provider share of total industry revenue, 2022–2023. Table developed based on Dell'Oro estimates published March 2024.**[36, 37]

Dell'Oro estimates that US suppliers earned 16% of total revenue in the global telecom equipment market in 2022, particularly in the broadband access, optical transport, and service provider router segments, but had less than 1% revenue share of the global RAN market.[38] In 2023, the global RAN market shrank roughly 10% following a pullback in network operator equipment spending in North America and Europe, both of which are several years into 5G network deployment.[39,40]

34 What is the state of US RAN and non-RAN suppliers? Dell'Oro contributed to Fierce Network, April 2023. https://www.fierce-network.com/wireless/what-state-us-ran-and-non-ran-suppliers-pongratz

35 Developed based on Dell'Oro estimates, March 2024. https://www.delloro.com/worldwide-telecom-equipment-market-slumps-in-2023/

36 Dell'Oro defines the telecom equipment market as: Broadband Access, Microwave and Optical Transport, Mobile Core Network and RAN, Service Provider Routers and Switches.

37 Using the revenue share information in Figure 5, telecom equipment market HHI for the top 5 players in 2022 and 2023 is 1351 and 1451, respectively. For more on HHI, see HHI estimates for the RAN supplier market on the next page.

38 US-domiciled telecom equipment suppliers include Corning, Cisco, Juniper, Motorola Solutions, Mavenir, Microsoft, Oracle, Adtran, Airspan, Aviat, Calix, Cambium, Casa Systems, Celona, Ciena, CommScope, DZS, Harmonic, HPE, Infinera, JMA Wireless, Parallel Wireless, and Ribbon. Source: Dell'Oro, 2023

39 Worldwide telecom equipment market slumps in 2023; Dell'Oro, March 2024. https://www.delloro.com/worldwide-telecom-equipment-market-slumps-in-2023/

40 Global RAN market declined by 11% in 2023, Telecoms, February 2024. https://www.telecoms.com/wireless-networking/global-ran-market-declined-by-11-in-2023

Leading RAN equipment suppliers are Huawei, Ericsson, Nokia, ZTE, and Samsung.[41] Additional RAN suppliers include NEC, Fujitsu, Mavenir, Rakuten Symphony, and CICT Datang Mobile.[42] There has historically been regionality in company revenue share. This was amplified after the United States placed ZTE and Huawei on trade blacklists in 2018 and 2019,[43] and US allies such as the United Kingdom, Japan, and Australia followed with similar actions. The inaugural Prague 5G Security Conference, held in the Czech Republic in May 2019 and featuring attendees from 32 countries, had a similar catalyzing impact in inducing operators from participating countries to reassess use of network equipment supplied by Huawei or ZTE in their home market networks.[44]

The RAN market is highly concentrated. Dell'Oro estimates that the top five RAN suppliers (Huawei, Ericsson, Nokia, ZTE, Samsung) captured 95.2% of revenue share in 2022, slightly down from 2021 (95.8%); Omdia estimates the top five suppliers captured 94.6% of revenue in 2022. Dell'Oro estimates that the market grew slightly more concentrated in 2023.

The Herfindahl-Hirschman Index (HHI) is a measure of industry concentration.[45] Using Dell'Oro estimates of top five RAN supplier revenue share, we calculate HHI for the RAN supplier market for the years 2021 and 2022 as 2269 and 2229, respectively. The overall HHI score declined slightly year-over-year, due to a slight redistribution of share between the top five RAN suppliers. Still, the RAN market remains concentrated overall. The US Department of Justice, in guidelines updated in January 2024, considers markets with HHI scores in excess of 1800 to be highly concentrated.[46]

41 The author referred to both Dell'Oro and Omdia research in assessing RAN provider market share. In addition, the author referred to Dell'Oro's Mobile RAN report, Q2 2023, purchased in summer 2023.

42 CICT Datang Mobile is a Chinese RAN supplier that provides radio and baseband products primarily to operators in the China market. Omdia research describes the company as an "upcoming" vendor, along with NEC, Airspan, and Fujitsu.

43 The Secure and Trusted Communications Networks Act was passed by Congress in 2019. The FCC created a $1.9 billion reimbursement program to help smaller carriers "rip and replace" equipment provided by ZTE or Huawei.

44 About the Prague 5G Security Conference, May 2019. https://vlada.gov.cz/en/media-centrum/aktualne/prague-5g-security-conference-173333/

45 US Dept of Justice, Herfindahl-Hirschman Index, January 2024. https://www.justice.gov/atr/herfindahl-hirschman-index

46 A market with one supplier with 100% market share would have a score of 10,000. Passenger air travel, which has two dominant suppliers, Airbus and Boeing, has an HHI score of 5200. For more, see: https://sites.lsa.umich.edu/mje/2024/05/08/comacs-impact-on-the-future-of-the-airbus-boeing-duopoly/

# Major RAN suppliers and their operating segments

While Nokia and Ericsson have spun off their handset divisions, Huawei, Samsung, and ZTE retain handset businesses and are more diversified companies with larger R&D budgets. Samsung, Huawei, and ZTE also have semiconductor business units. Samsung is among the global leaders in semiconductors, not only in market share (e.g., in the memory market), but also in semiconductor fabrication, as measured by process node generations. Samsung has an estimated 11% revenue share in the semiconductor fabrication market, compared to TSMC's 62%.[47] Samsung had a 45% share in the DRAM memory market as of Q4 2023.[48]

Huawei, Ericsson, Nokia, and Samsung Electronics segment revenue is presented in Figures 6 through 9.

| Huawei revenue | 2022 | 2023 |
|---|---|---|
| ICT infrastructure | $48,825 | $49,931 |
| Consumer | $29,581 | $34,689 |
| Cloud Computing | $6,254 | $7,626 |
| Digital Power | $7,008 | $7,256 |
| Intelligent Automation Solutions | $286 | $653 |
| Other | $549 | $1,190 |
| Elimination | $(3,904) | $(4,217) |
| Total | $88,598 | $97,127 |

**Figure 6: Huawei segment revenue, converted from CNY into USD millions.**

Huawei, headquartered in Shenzhen, China, includes RAN products in its ICT infrastructure unit, which includes products for multiple end markets, such as network operators, enterprise, retail, manufacturing, education, and other end markets.[49]

47 Share estimates from TrendForce, via Statista, as of Q1 2024. Estimates include legacy semiconductor nodes.

48 Samsung holds DRAM market supremacy, Korea Economic Daily, February 2024. https://www.kedglobal.com/korean-chipmakers/newsView/ked202402270014

49 Source: Huawei 2023 annual report.

| Ericsson AB | 2022 | 2023 |
|---|---|---|
| Networks | $18,356 | $16,264 |
| Cloud Software & Services | $5,742 | $6,037 |
| Enterprise | $1,385 | $2,443 |
| Other | $281 | $240 |
| Total | $25,763 | $24,986 |

**Figure 7: Ericsson segment revenue, converted from SEK into USD millions.**

Ericsson AB, headquartered in Stockholm, Sweden, includes RAN products in its Networks unit, which also includes transport products and IPR licensing revenues.

| Nokia Oyj revenue | 2022 | 2023 |
|---|---|---|
| Network Infrastructure | $9,861 | $8,760 |
| Mobile Networks | $11,631 | $10,679 |
| Cloud and Network Services | $3,653 | $3,510 |
| Nokia Technologies | $1,739 | $1,183 |
| Group Common and Other | $322 | $142 |
| Eliminations and Unallocated Items | $(52) | $(12) |
| Total revenues | $27,153 | $24,261 |

**Figure 8: Nokia segment revenue, converted from Euros into USD millions.**

Nokia Oyj, headquartered in Helsinki, Finland, reports revenue from IP routing, optical and fixed networks, and submarine networks in its Network Infrastructure segment.[50,51] RAN products are reported in its Mobile Networks segment, along with transport network products (e.g., microwave radios).

50 Revenue from Nokia 2023 annual report.

51 In June 2024, Nokia announced an agreement to sell 80% of its Alcatel Submarine Networks units to the government of France. Nokia had acquired the group with its acquisition of Alcatel-Lucent in 2016. Alcatel and Lucent merged in 2006. Thus, Nokia is the current owner of Bell Labs. For more on Nokia's sale of ASN: https://www.nokia.com/about-us/news/releases/2024/06/27/nokia-enters-into-an-agreement-with-the-french-state-regarding-the-sale-of-leading-submarine-networks-business-asn/

| Samsung Electronics | 2022 | 2023 |
|---|---|---|
| Device Experience (DX) | $132,645 | $123,561 |
| DS | $71,563 | $48,405 |
| SDC | $24,991 | $22,515 |
| Harman | $9,605 | $10,458 |
| Internal Adjustment, Etc. | $(19,124) | $(16,729) |
| Total | $219,680 | $188,210 |

**Figure 9: Samsung Electronics segment revenue, converted from KRW into USD millions.**

Samsung Electronics' Device Experience unit includes its Mobile eXperience (MX) / Networks segment and Visual Display (e.g., TVs) product segment. MX / Networks includes both smartphones and infrastructure products such as RAN products.[52] Samsung reports semiconductor industry revenue in its DS (Device Solutions) segment, which includes memory and related products, system LSI revenue, and fabrication revenue. Display products such as OLED screens, both for Samsung handsets and external customers, are reported in Samsung's SDC (Samsung Display) segment. Samsung acquired Harman in 2016 and continues to report it as a separate segment.

52 Revenue from Samsung investor relations and Capital IQ. RAN segment revenue estimates from Dell'Oro.

# Major RAN providers, their silicon capabilities, and R&D expenditures

RAN equipment uses two key kinds of chips: products for digital networking, and analog products such as RF (radio frequency) transceivers and RF filters and converters. Key providers of analog chip products include Analog Devices and Texas Instruments.[53] Key providers of networking products include Qualcomm and Marvell.

Huawei retains its own semiconductor design unit, HiSilicon, and both reporting and investor relations data indicate it is investing in internalizing its own chip fabrication capabilities, in addition to partnering with Shanghai-based fabrication specialist SMIC.[54]

Samsung Electronics provides both logic and memory products to internal and external customers and also operates a semiconductor fabrication business that makes chips on behalf of external customers.

While both companies have long since exited the handset business, Nokia and Ericsson both retain silicon design capabilities for their RAN products. Ericsson designs its own custom-made chips for traditional RAN products.[55] It partners with Intel for processors for its cloud RAN products, and for manufacture of SoC (system-on-chip) products for traditional RAN products.[56,57] Nokia partners with Marvell for custom chips for its 5G RAN products.[58]

## KEY NETWORK EQUIPMENT SUPPLIER R&D EXPENDITURES

We described earlier the relationship of co-specialization between network operators and network equipment providers. Network operators will often work with more than one key supplier

53 Analog Devices Eyes Bigger Role in 5G Base Stations With Radio SoC, Electronic Design, February 2022. https://www.electronicdesign.com/technologies/analog/article/21183443/electronic-design-analog-devices-eyes-bigger-role-in-5g-base-stations-with-radio-soc

54 Huawei building vast chip equipment R&D center in Shanghai, Nikkei Asia, April 2024. https://asia.nikkei.com/Business/Tech/Semiconductors/Huawei-building-vast-chip-equipment-R-D-center-in-Shanghai

55 Ericsson, Cutting edge innovation on a chip. Accessed July 2024. https://www.ericsson.com/en/ran/ericsson-silicon

56 Ericsson's cloud RAN affair with Intel is a puzzle, Light Reading, November 2023. https://www.lightreading.com/semiconductors/ericsson-s-cloud-ran-affair-with-intel-is-a-puzzle

57 While stating that it partners with Intel to use Intel CPUs for cloud RAN products, Ericsson's operator marketing collateral touts the efficiency benefits of its own custom silicon. For example: https://www.ericsson.com/en/ran/ericsson-silicon

58 Nokia and Marvell enter into partnership on silicon technology for 5G; Nokia, March 2020. Accessed July 2024. https://www.nokia.com/about-us/news/releases/2020/03/04/nokia-and-marvell-enter-into-partnership-on-silicon-technology-for-5g/

as prime suppliers, often awarding "prime status" to a key supplier within a given region, with another key supplier given prime status in a different region. For example, in the US market, AT&T works with Ericsson and Nokia as prime suppliers. These prime suppliers are responsible for integrating products from other suppliers. This puts long-time incumbent suppliers in a position of trust. It also means they have a stake in what innovation is deployed in operator networks and have an intermediary relationship. This can create a potential barrier to entry to new suppliers.[59] It also means that network operators, having assigned large portions of their networks to prime supplier partners, have a stake in the ability of these established network equipment suppliers to continue to innovate.

For example, in the United States, the former "Big Four" network operators (AT&T, Sprint, T-Mobile USA, and Verizon) have become the Big 3 following the merger of T-Mobile USA and Sprint, which was completed in 2020. The three operators have largely sourced their 5G network equipment from established incumbent suppliers Ericsson, Nokia, and Samsung. All three US network operators buy from Ericsson. Thus, it is no exaggeration to say the US mobile ecosystem, and the connected economy more generally, is dependent on Ericsson's ongoing ability to innovate.

Traditional (non-greenfield) network operators will often have multiple network generations (e.g., 3G, 4G, and 5G) running concurrently. With the rollout of 5G networks, this led to incumbent operators pairing 5G RAN with 4G Core. While done for economic reasons, and also because the migration of existing subscribers to new 5G handsets takes time (the handset upgrade rate in the US and many other smartphone-centric markets is roughly once every three years), this too can perpetuate supplier incumbency. If pairing 5G RAN with 4G Core, the incumbent provider of 4G RAN and Core products has a favorable position, both for 5G RAN products and subsequent 5G Core products.

However, network generational upgrades can be a point of entry for new suppliers. This was the case for Huawei with 3G and 4G, for example, as Huawei's dramatic global market share growth came during 3G and 4G network deployments.[60] In the US market, Samsung grew its

59 As an example of this intermediary role, in 2013, on behalf of a major Asian communications equipment provider, the author assessed potential operator demand in the US market for greenification of power for mobile networks. It was made clear during interviews with US operators that integration with incumbent network equipment suppliers would be required. Incumbent network equipment suppliers, of course, had no incentive to collaborate with a new supplier partner unless ordered to do by network operator customers.

60 Gartner estimates that Huawei had 11% market share in 2008, compared to a current estimated share of 30% in 2023.

business with Verizon during its 5G rollout, possibly at the expense of Nokia, which was a 4G supplier to Verizon.[61]

In December 2023, AT&T announced that it expected to move 70% of mobile traffic to "open infrastructure" by 2026,[62] as part of an announcement of a five-year network contract with Ericsson.[63] Reporting and interviews indicate that this came at the expense of incumbent supplier Nokia, and Ericsson is removing recently deployed Nokia equipment from AT&T's 5G network as part of the arrangement.[64] AT&T plans to deploy radio (RU) products from Fujitsu as part of this new deployment, with Ericsson functioning as the integrator of Fujitsu products, along with Ericsson's own RU products.[65] Other reported suppliers to AT&T include Dell, Intel, Microsoft (Azure), and Rakuten Symphony.[66] In December 2024, Mavenir was also announced as a supplier. The AT&T-Ericsson arrangement will increase the co-dependence between AT&T and Ericsson, which already had an estimated 60–65% share within AT&T's network.

R&D expenditures from 2010–2022 by Nokia, Ericsson, Huawei, Samsung, and Qualcomm are shown in Figure 12. (As of July 2024, 2022 was the most recent year for which data was available for Huawei, which is privately held; the other four companies are publicly traded.) The drop in Nokia's R&D in 2011 corresponds with the sale of its handset segment to Microsoft. The increase in Nokia R&D expenditures in 2016 corresponds with the acquisition of Alcatel-Lucent.

As of 2010, Nokia and Huawei's R&D expenditures were roughly equivalent. As of today, the individual R&D budgets of Huawei and Samsung are greater than those of Nokia and Ericsson combined. This is not an apples-to-apples comparison, however: Samsung and Huawei both retain handset businesses; Samsung is a leading semiconductor provider and fabricator. Huawei is a more diversified company and is investing heavily in vertical integration after being put in a trade blacklist in 2019 and since US Department of Commerce Bureau of Industry and Security

61 Verizon boots Nokia, Samsung gets the spoils, SDX Central, July 2020. https://www.sdxcentral.com/articles/news/verizon-boots-nokia-samsung-gets-the-spoils/2020/07/

62 A major step toward Open RAN in the United States, AT&T, December 2023. https://www.attconnects.com/a-major-step-toward-open-ran-in-the-united-states/

63 AT&T to Accelerate Open and Interoperable Radio Access Networks (RAN) in the United States through new collaboration with Ericsson, AT&T, December 2023. https://about.att.com/story/2023/commercial-scale-open-radio-access-network.html?source=EB00C0000000000L

64 Inside AT&T's Nokia rip-and-replace with Ericsson, Light Reading, July 2024. https://www.lightreading.com/open-ran/inside-at-t-s-nokia-rip-and-replace-with-ericsson

65 Author interviews, spring 2024

66 Inside AT&T's Nokia rip-and-replace with Ericsson, Light Reading, July 2024. https://www.lightreading.com/open-ran/inside-at-t-s-nokia-rip-and-replace-with-ericsson

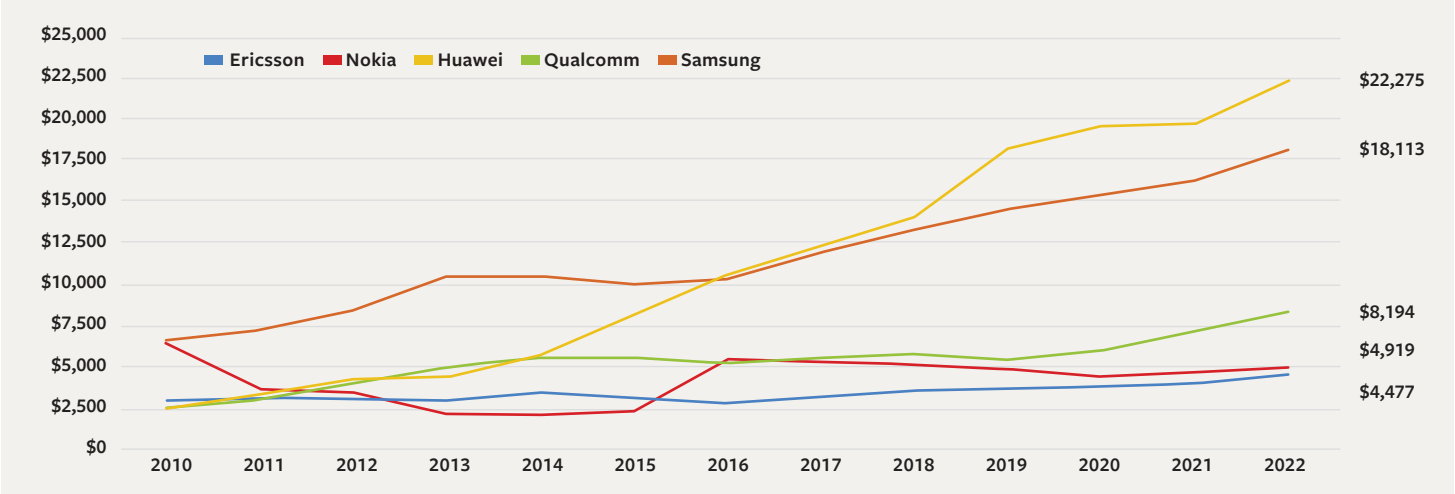


**Figure 10: Research and development (R&D) expenditures for Nokia, Ericsson, Huawei, Samsung, and Qualcomm, 2010–2022. Based on data available as of July 2024.**

sanctions limiting access to key technologies began in 2022.[67] Huawei states it spent 23% of revenue on R&D in 2023. But Huawei's increased R&D expenditures show the benefits of a flywheel — more market share enables more revenue, enabling more R&D expenditures — and pose an important question: can long-time key network equipment suppliers such as Nokia and Ericsson continue to innovate?[68]

Nokia and Ericsson are hardly skimping on R&D investment. Nokia spent roughly 18% of revenue on R&D in 2022, and Ericsson invested 17.4% of 2022 revenue into R&D. Apple, by comparison, spent 8% of revenue on R&D (TTM), and Samsung spent 11% in 2023. Still, the difference in absolute terms in expenditures is striking — Huawei spent over $22 billion in R&D in 2022, whereas Nokia spent a little under $5 billion in R&D.

## MERCHANT SILICON PROVIDES PRECEDENT FOR THE RAN MARKET

A similar dynamic unfolded in the mobile baseband supplier market in the 1990s and 2000s: Qualcomm's success as a provider of "merchant silicon" to handset makers both enabled new

67 US Dept. of Commerce, Bureau of Industry and Security, Federal Register notice, October 13, 2022. https://www.bis.doc.gov/index.php/documents/federal-register-notices-1/3165-87-fr-62186-advanced-computing-and-semiconductor-manufacturing-items-rule-published-10-13-22/file

68 In 2019, WSJ reporting assessed that Huawei had benefited from a combined $75 billion in various forms of subsidy, from discounted land purchases to customer financing from 1998 to 2018, including $15.7 billion in state loans, export credits, or other forms of financing (for Huawei or for customers), and $30.6 billion in credit availability from China policy banks.

handset makers that didn't have captive semiconductor arms to enter the handset market, and benefit from Qualcomm's growing R&D. Qualcomm's entry also put pressure on incumbent handset makers with captive semiconductor arms (e.g., Motorola, NEC, and Panasonic) to try to keep pace with Qualcomm's innovation, without the benefit of Qualcomm's greater scale. Qualcomm could sell to any handset manufacturer; Motorola, NEC, or Panasonic, by contrast, could only sell to their own handset group. This advent of merchant silicon led to a dramatic shift in the handset market. Whereas early (2G GSM era) handset leaders such Motorola or Siemens were part of vertically integrated companies that also provided network equipment, handsets, and semiconductors, 3G and 4G leaders, at least in Western markets, were often pure-play handset manufacturers that sourced silicon from partners like Qualcomm.

Ultimately Motorola spun out its semiconductor arm as Freescale; Philips spun out its semiconductor arm as NXP; and those two companies later merged in 2015.[69,70,71] Many of Japan's various handset companies consolidated their semiconductor businesses into what is now Renesas Electronics.[72]

It is an example that is analogous to the RAN segment today, given the dramatic split in R&D expenditures between suppliers. It is noteworthy that Nokia Networks has, over the years, absorbed network businesses from Siemens, Motorola Solutions, and Alcatel-Lucent.[73] Nokia's relatively slimmer R&D expenditures (in absolute dollars, compared to those of Huawei) come even after substantive consolidation in the network equipment supplier market. In March 2022, Nokia announced that it would continue slimming headcount, which peaked in 2017 following the acquisition of Alcatel Lucent, and invest the savings in R&D.[74] However, Nokia reduced its R&D budget slightly during the year ending in March 2024.[75]

69 Motorola SPS becomes Freescale Semiconductor, EE Times, February 2004. https://www.eetimes.com/motorola-sps-becomes-freescale-semiconductor-4/

70 Philips Semiconductor to become NXP, EE Times, August 2006. https://www.eetimes.com/philips-semiconductors-to-become-nxp/

71 NXP and Freescale Announce $40 Billion Merger, NXP, March 2015. https://www.nxp.com/company/about-nxp/nxp-and-freescale-announce-40-billion-merger:NW-FREESCALE-40BILLION-MERGE

72 NEC Electronics and Renesas to integrate business operations, April 2009. https://www.hitachi.com/New/cnews/f_090427b.pdf

73 Nokia Siemens Networks completes acquisition of certain wireless network infrastructure assets of Motorola Solutions, Nokia, April 2011. https://www.motorolasolutions.com/newsroom/press-releases/nokia-siemens-networks-completes-acquisition-certain-wireless-network-infra.html

74 Nokia still has up to 8K jobs to cut after slow progress on turnaround, Light Reading, February 2022. https://www.lightreading.com/5g/nokia-still-has-up-to-8k-jobs-to-cut-after-slow-progress-on-turnaround#

75 Ericsson and Nokia face R&D threat amid telco spending slump, Light Reading, January 2024. https://www.lightreading.com/finance/ericsson-and-nokia-face-r-d-threat-amid-telco-spending-slump

In sum, operators in countries that have restricted use of Huawei or ZTE have a limited set of suppliers to choose from. This has given some longstanding suppliers that have limited global RAN market revenue share, such as Samsung, NEC and Fujitsu, hope that they can grow their businesses outside of their respective home markets. It has also put policymakers' hopes on Open RAN.

# Enter Open RAN?

The high level of concentration in the network equipment supplier market, and the dynamic of network operator-network equipment supplier co-specialization described thus far in this report, provide the backdrop for Open RAN.

Open RAN refers to a movement to unbundle the RAN, i.e., to: (a) disaggregate what historically had been monolithically provided by one supplier; (b) facilitate greater interoperability between supplier hardware and software; and (c) create greater supplier diversity in the RAN market. Both policymakers and network operators interviewed for this report have described their goals for Open RAN as being able to provide (or source from) alternatives to traditional suppliers. For example, multiple interviewees commented that in a policy or alliance context, if the United States wants allies to not buy from Huawei or ZTE, then it should be able to provide more alternatives than Ericsson or Nokia.[76] It is important to note that traditional RAN suppliers such as Nokia and Ericsson are also themselves suppliers of Open RAN or Open RAN-ready products.

It is noteworthy, though, that even before geopolitics were involved, the high levels of concentration of RAN suppliers led network operators in multiple different regions in the world to investigate Open RAN as a means of nurturing alternatives to current suppliers. Indeed, network operators in China were among the early backers of Open RAN (through the C-RAN Alliance, founded in 2016), due to their high level of dependence on Huawei and ZTE.

We note further that the short-term impact of geopolitics on the RAN market has been to increase concentration on a narrowed set of trusted suppliers. Rephrased, network operators that might have invited Huawei to respond to an RFP as a way to get better prices out of Nokia have lost that ability. Another impact of trade blacklists and Open RAN has been to provide longstanding network suppliers with relatively smaller global market shares, such as Samsung, NEC, and Fujitsu, a new opportunity to expand their share globally. These three companies together now have roughly 10% combined share in the RAN market, with the bulk of that going to Samsung.

## SO WHAT DOES OPEN RAN UNBUNDLE?

4G networks divided the RAN into two components: the Remote Radio Head (RRH, sometimes referred to as the Remote Radio Unit) and the Baseband Unit (BBU). These are con-

76 This point has been consistently made in multiple policymaker and network operator interviews conducted by the author over the course of research for this paper, including with White House NSC staff.

nected using the CPRI interface, and may be connected by fiber, depending on deployment.[77] Much as the Base Station Controller (BSC) in 2G networks might control more than one Base Transceiver Station (BTS), one BBU may control more than RRH.[78] This disaggregation of RRH and BBU was described by 3GPP, the global standards body governing cellular standards.

With 5G, this disaggregation has continued, dividing the RAN into three products: RU, DU, and CU:

- Radio Unit: Located at the cell site near the antenna, the radio unit transmits, receives, amplifies, and digitizes RF signals.
- Distributed Unit: Located at or near the RU, the distributed unit provides real-time processing for lower-layer networking before sending digitized signals into the network. The DU may handle multiple RUs.
- Control Unit: The CU handles additional processing, potentially for multiple DUs, before sending digitized signals into the network. The CU can be regionally distributed, such as in a data center or telco central office, unlike DUs, which need to be located near a cell site or in an edge cloud closer to the RU, generally within a range of 20km.[79]

This increased disaggregation of the RAN is described in Figure 11, a diagram from Open RAN supplier Parallel Wireless. The RU is what connects with the user device, such as a smartphone.

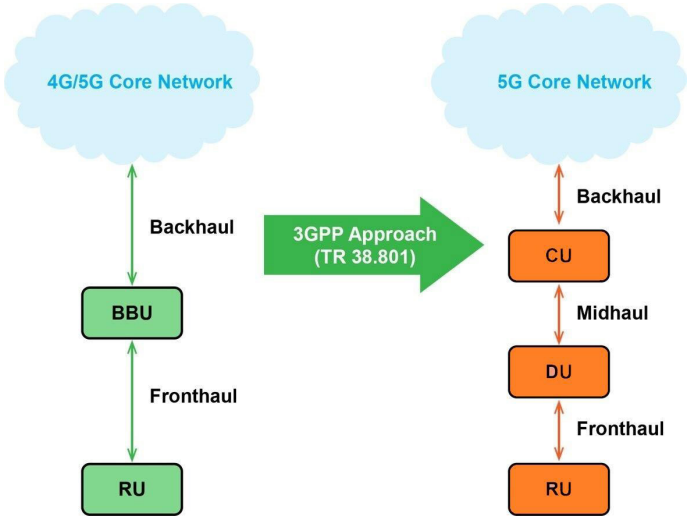


**Figure 11: 4G and 5G RAN nodes and interconnections. Diagram by Parallel Wireless.**[80]

77 Remote Radio Head In 5G NR, RF Wireless World. Accessed July 2024. https://www.rfwireless-world.com/Articles/Remote-Radio-Head-in-5G-NR-system.html

78 2G GSM networks comprised the BTS (Base Transceiver Station), Base Station Controller (BSC), and Mobile Switching Center (MSC). These roughly correspond to the RU, DU, and CU in 5G. In enterprise wireless networks, these are roughly analogous to WLAN (wireless LAN) access points, controllers (which control multiple access points), and switches (which may manage multiple controllers).

79 List developed based on Nokia, Rakuten, Xilinx, and other industry sources, including: Open RAN 101, RCR Wireless, July 2020. Accessed July 2024. https://www.rcrwireless.com/20200708/fundamentals/open-ran-101-ru-du-cu-reader-forum

80 Open RAN functional splits explained, Parallel Wireless contributed article to 5G Technology World, July 2021. Accessed July 2024. https://www.5gtechnologyworld.com/open-ran-functional-splits-explained/

3GPP, referred to in the diagram, refers to the Third Generation Partnership Project, which was founded in 1998 to create a globally harmonized 3G standard.[81] 3GPP has defined subsequent generations of mobile network technology (e.g., 4G, 5G, etc.). The most recent major "frozen" 3GPP release is Release 18 ("5G Advanced"). Major releases are shown in Figure 12, a 3GPP diagram describing major releases corresponding to 3G, 4G, and 5G, and planned releases for 6G.[82] Pre-standardization study for 6G has begun as of 2024, per 3GPP, Ericsson, and other sources.[83,84]

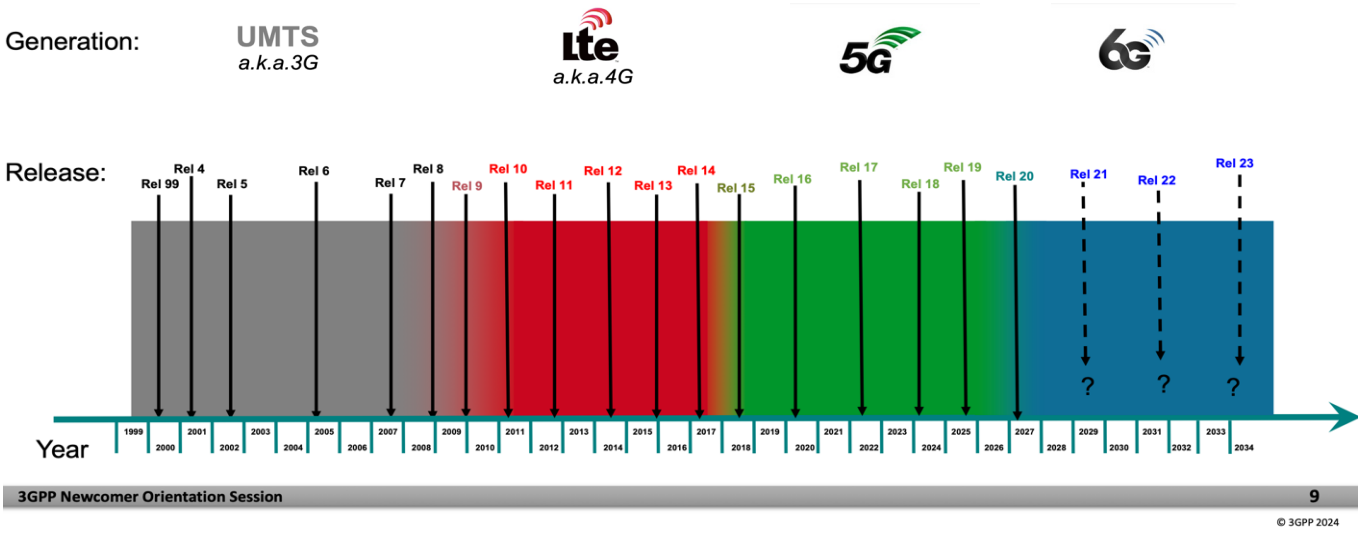


Figure 12: Major 3GPP releases

## CONVERGING ON OPEN RAN

Various industry organizations, separate from 3GPP, have converged on what is now generally referred to as Open RAN or O-RAN. A timeline of these different organizations is provided below.

81 About 3GPP: The 3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as "Organizational Partners" and provides its members with a stable environment to produce the reports and specifications that define 3GPP technologies. https://www.3gpp.org/about-us/introducing-3gpp

82 3GPP newcomers "quick start" guide, June 2024. 3GPP presentation, accessed July 2024. https://www.3gpp.org/ftp/Information/presentations/Newcomers_quick-start/Newcomers_slides.pdf

83 Three 3GPP Chairs Clarify 6G Standard Release Timeline at Global 6G Conference, April 2024. https://en.g6gconference.com/index/Details/index.html?id=312

84 6G standardization — an overview of timeline and high-level technology principles, Ericsson, March 2024. https://www.ericsson.com/en/blog/2024/3/6g-standardization-timeline-and-technology-principles

- 2016: Facebook launched the Telecom Infra Project (TIP).[85] Facebook's goals were to help lower the cost of mobile connectivity, and help extend connectivity into unserved or underserved regions and economies. TIP member activity focuses on three areas: Access (subscriber connecting infrastructure); Transport (backhaul); and Core & Services. As of July 2024, TIP has working groups focused on Fixed Broadband; Metaverse-Ready Networks; Neutral Host & Infra Sharing; Open Optical and Packet Transport; OpenLAN; OpenRAN; and TelcoAI. Working groups that have reached the end of their initial charters "graduate" and publish their findings.[86]
- 2018: The O-RAN Alliance was founded in February 2018[87] by network operators AT&T, China Mobile, Deutsche Telekom, NTT DOCOMO, and Orange, and now has more than 300 members. The Alliance is operator-led, with a board of directors composed of global network operator members. The O-RAN Alliance was a merger of two prior industry groups, the C-RAN Alliance and xRAN Forum, both founded in 2016.[88] The C-RAN Alliance (short for cloud-native RAN, or virtualized RAN) mainly included Chinese members; the xRAN Forum (named for software-based, extensible RAN) comprised international members from the United States, Japan, South Korea, and Europe. O-RAN Alliance network operator members are shown in the member list in Figure 13.[89]

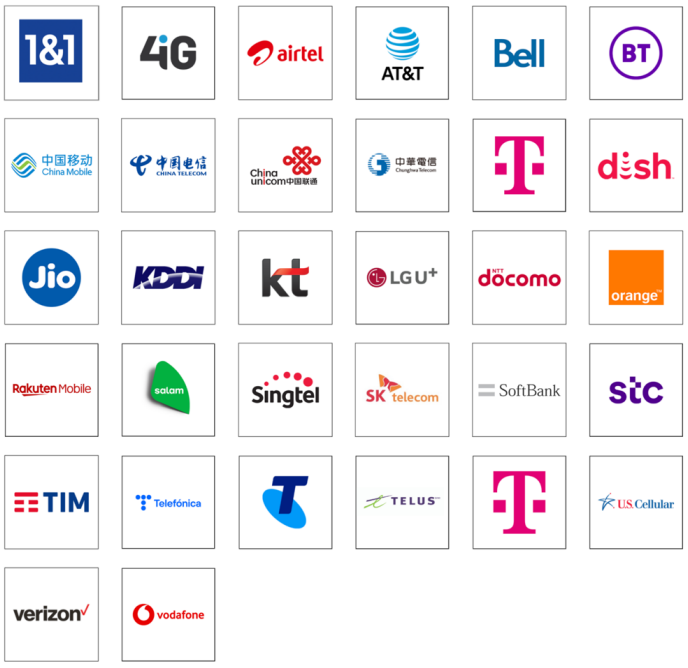


**Figure 13: O-RAN Alliance operator members as of July 2024.[90]**

85 Meta, Introducing the Telecom Infra Project, February 2016. https://about.fb.com/news/2016/02/introducing-the-telecom-infra-project/

86 Telecom Infra Project, Project Groups. Accessed July 2024. https://telecominfraproject.com/exchange/project-groups/

87 https://www.o-ran.org/about

88 https://www.businesswire.com/news/home/20180227005673/en/xRAN-Forum-Merges-With-C-RAN-Alliance-to-Form-ORAN-Alliance

89 https://www.o-ran.org/membership

90 Members as of July 2024. https://www.o-ran.org/membership

O-RAN Alliance members include both traditional network operators, i.e., "brownfield" operators assessing Open RAN in the context of their incumbent networks, and new "greenfield" network operator members, such as Rakuten Mobile, DISH,[91] and 1&1, which have harnessed Open RAN to roll out new 4G/5G networks that take advantage of network virtualization techniques. While greenfield operators face a cold start problem on many dimensions, from customer acquisition, to building supplier relationships, to getting to sufficient scale to get a return on their investments, they have the advantage of not needing to support legacy 2G/3G features required in supporting traditional incumbent network operators.

Both the O-RAN Alliance and TIP exist separately from and engage in standards development work in parallel to 3GPP, and also separate from network operator associations such as GSMA. In 2020, TIP and the O-RAN Alliance announced an alliance on 5G RAN solutions, and GSMA and the O-RAN Alliance announced collaboration to open up 5G networks.[92, 93]

Within the broader topic of Open RAN, multiple terms are used:

- Open RAN refers to unbundling the RAN into Radio Unit (RU), Distributed Unit (DU), and Control Unit (CU) products. In a technical sense, it means standardizing and publishing the interfaces between these products.
- Cloud RAN refers to putting elements of the RAN, such as the CU, in the cloud.
- Virtualized RAN, or vRAN, refers to virtualization of either DU or CU (vDU or vCU) products. Virtualized RAN products represented about 2.5% of the total RAN market in 2022.[94]

The virtualization of elements of the RAN is similar to what has happened with WLAN (wireless LAN, or Wi-Fi) products, where some providers, such as Meraki and Aerohive, moved WLAN controller products to the cloud in the early 2010s. (Cisco acquired Meraki in 2012.[95]) Wi-Fi access points themselves remain at the customer premise. More recently, this has occurred in the security camera segment; security cameras themselves remain on-premise, at an office or corporate campus, but some providers have moved controller products to the cloud. These

91 Dish now operates as Boost Mobile.

92 The O-RAN Alliance and the Telecom Infra Project (TIP) Reach New Level of Collaboration for Open Radio Access Networks, February 2020. https://www.businesswire.com/news/home/20200225005180/en/O-RAN-Alliance-Telecom-Infra-Project-TIP-Reach

93 GSMA and O-RAN Alliance Collaborate on Opening up 5G Networks, May 2020. https://www.gsma.com/newsroom/press-release/gsma-and-o-ran-alliance-collaborate-on-opening-up-5g-networks/

94 Dell'Oro Mobile RAN report, Q2 2023.

95 Cisco Completes Acquisition of Meraki, Cisco Systems, December 2012. https://newsroom.cisco.com/c/r/newsroom/en/us/a/y2012/m12/cisco-completes-acquisition-of-meraki.html

similarities are likely why companies traditionally involved in enterprise IT, such as Dell and NEC, invested in developing offerings for the Open RAN market.

While Open RAN proposes opening interfaces between RAN components to allow use of heterogenous suppliers (e.g., separate suppliers for RU and DU products), the number of operators that have implemented multi-vendor RAN is still relatively limited. Some operators, such as Verizon, have announced they are "Open RAN-ready," which means that suppliers have adopted standardized interfaces at Verizon's request, but Verizon has not actually implemented multi-vendor RAN.[96] Operators that have implemented multi-vendor RAN include Rakuten Mobile and NTT DOCOMO in Japan, and Vodafone in the UK. In the US, AT&T plans to use Fujitsu radios along with Ericsson radios, most likely with Ericsson basebands. DISH, in its limited 5G deployment in the US, has paired Fujitsu and Samsung radios with Mavenir and Samsung DUs.[97]

In all cases, an integrator is required to stitch the unbundled network elements back together. This integrator can be the network operator itself; a network equipment supplier; or a third party, such as an IT services provider. Some network operators, such as Rakuten Mobile (Rakuten Symphony) and NTT DOCOMO (OREX), have stood up service organizations building on their own experiences with multi-vendor RAN, with the goal of assisting other network operators with multi-vendor RAN deployments.

## OPEN RAN TESTING AND STANDARDIZATION

The O-RAN Alliance runs testing and integration centers; provides a product certification function; and also holds "PlugFests", i.e., exhibitions for members to exhibit their products. It also provides an updated map displaying Open RAN deployments in varying stages, from MoU to testing to full commercial deployment, as shown in Figure 14.[98]

The O-RAN Alliance also engages in standards development work to ensure interoperability between different providers. This activity is divided across 11 workgroups. Examples include WG1: Use Cases and Overall Architecture Workgroup; WG4: Open Fronthaul Interfaces Workgroup; and WG11: Security Workgroup. There are two additional focus groups looking at Test and Integration, and at Sustainability.[99, 100]

96 https://www.lightreading.com/open-ran/verizon-embraces-open-ran-messaging
97 https://www.fcc.gov/ecfs/document/10714483010865/1
98 https://map.o-ran.org
99 https://specifications.o-ran.org/specifications
100 5G Americas provides a white paper: *Transition Toward Open & Interoperable Networks*, 2020. https://www.5gamericas.org/wp-content/uploads/2020/11/InDesign-Transition-Toward-Open-Interoperable-Networks-2020.pdf

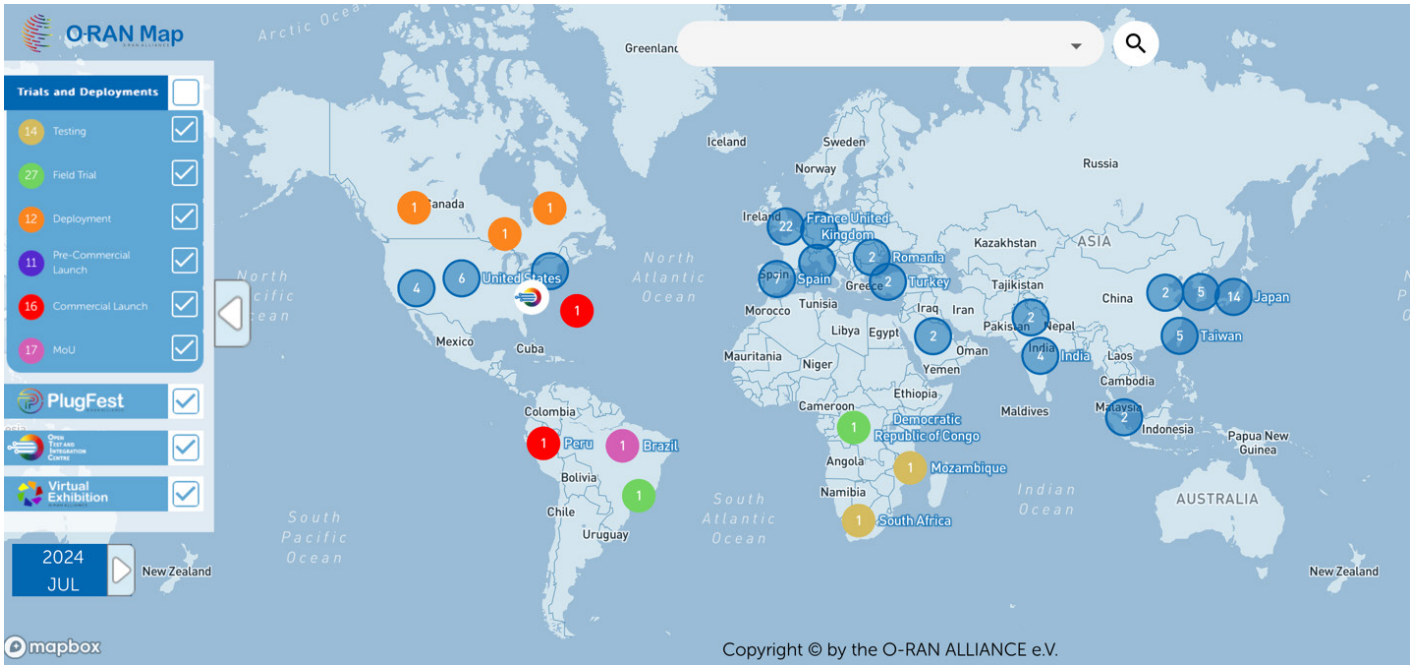


**Figure 14: Map of Open RAN deployments, as of July 2024.**

Unbundling the RAN into three different elements (RU, DU, and CU), potentially from heterogenous suppliers, requires defining which network functions will be handled by which element, and specifying the interfaces between the different elements. This allocation of different network features across different network elements is referred to as "RAN functional splits."[101]

Figure 15, from 3GPP TR 38.801, describes Layer 1, Layer 2, and Layer 3 networking functions and whether they would be handled by the RU, DU, or CU.[102] In total, 3GPP describes eight options for functional splits between different elements in the RAN.

In making the decision on which RAN element should have what level of functionality, a network operator faces a number of cost/benefit calculations, such as equipment cost and complexity; availability of connectivity options between network elements (e.g., Ethernet or fiber); and the number of RU and DU sites required, as well as the number of RU supported by one DU, which can influence rent, energy, and maintenance costs.

101 For a detailed explainer on 5G functional splits: https://www.5gtechnologyworld.com/functional-splits-the-foundation-of-an-open-5g-ran/

102 For an explanation of the OSI model and its seven layers: https://aws.amazon.com/what-is/osi-model/

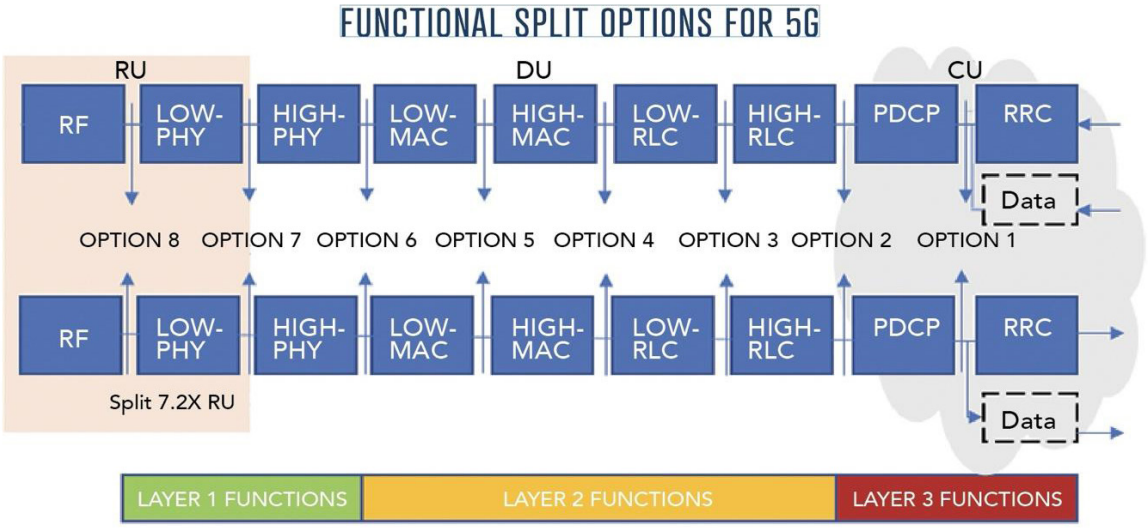


**Figure 15: RAN functional split options for 5G (accessed July 2024 via Parallel Wireless contributed article to 5G Technology World).**[103]

For example, a simpler RU with fewer features may cost less on a per-unit basis, but could also necessitate a more muscular DU and require more fronthaul traffic between RU and DU, which in turn could necessitate more fiber connectivity. Thus, an operator in a fiber-dense environment may be able to use existing fiber; if that fiber is not already available, supporting a lot of fronthaul deployment could necessitate more fiber install. Further, a simpler RU might necessitate more RUs if the network operator is supporting customers in a highly teledense area. This, in turn, could necessitate more site acquisition, and accordingly, more related rent, energy, and maintenance costs. Conversely, pushing more functionality on the DU could enable better load-balancing and sector resource management across multiple RUs. Again, for network operators, this is a multi-dimensional tradeoff. Equipment cost alone is not the sole determinant.

As a rule of thumb, network equipment costs may represent 15% of total operator cost of ownership over a 10-year lifespan, with energy, rent, civil costs, and maintenance being other cost influencers, as shown in Figure 16 "Why use Open RAN and vRAN," an illustrative diagram from analyst firm Dell'Oro.[104] Thus, a configuration that helps optimize rent and energy costs will be attractive to operators.

103 https://www.5gtechnologyworld.com/open-ran-functional-splits-explained

104 Interview, Dell'Oro Open RAN analyst Stefan Pongratz. Diagram courtesy of Stefan Pongratz.

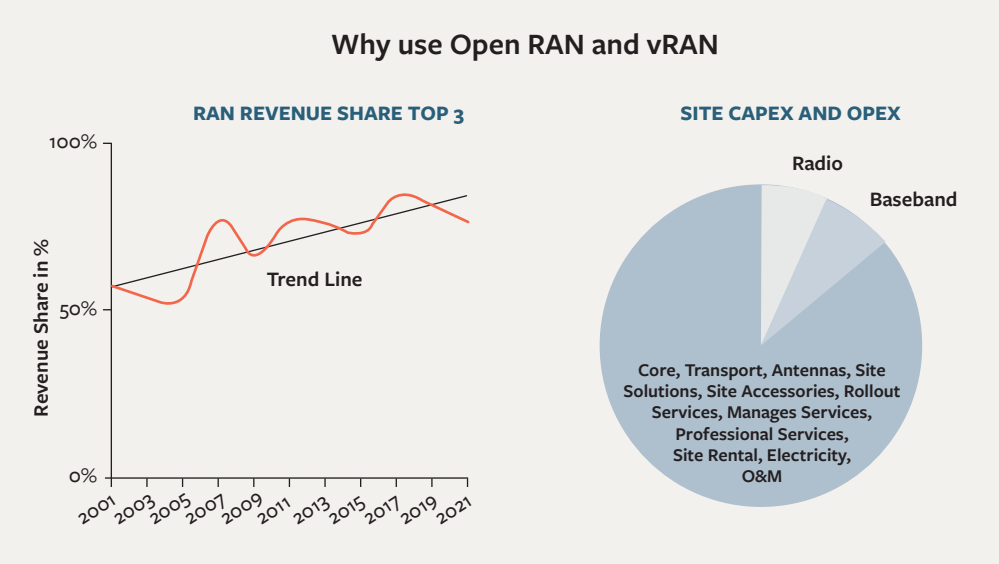


**Figure 16: Left: RAN revenue share of the top three RAN suppliers, 2001–2021; Right: site TCO (illustrative; describes contributors to both capex and operating expenses).**

Of the eight options for RAN functional splits described by 3GPP, the O-RAN Alliance settled on option 7.2x, which describes a relatively simple RU and utilizes compression to reduce bitrates needed between RU and DU, enabling use of Ethernet connectivity. However, in 2023, a consortium led by Ericsson proposed option 7.3, which pushes more features into the RU with the goal of improving better supporting MIMO deployments.[105]

There are legitimate technical and economic reasons for network operators to want this choice; while a 7.3 RU would likely be more expensive on a unit basis, an operator supporting customers in a teledense urban environment (i.e., the type of environment where massive MIMO would be relevant) may ultimately need fewer RUs, and thus potentially save overall on deployment and running costs. It is noteworthy that Ericsson's proposal drew support from operators AT&T and Orange. Still, another view is that Ericsson, one of the network equipment incumbents with much at stake, has succeeded in complicating the standards process at the O-RAN Alliance, which was founded to define interfaces between RAN elements more rigorously than 3GPP historically had.

105 MIMO: multiple input, multiple output. A MIMO RU can have 16x16 or even 64x64 transceiver configurations. https://www.ericsson.com/en/portfolio/networks/ericsson-radio-system/radio/macro/massive-mimo https://www.lightreading.com/open-ran/ericsson-and-pals-split-open-ran-community-with-massive-mimo-plan

## RAN NETWORK INTERFACES

Significant interfaces between network elements include:[106]

- Fronthaul: O-RAN Alliance specified. Interface between RU and DU (CPRI, eCPRI, Ethernet).
- Midhaul: 3GPP specified. F1 interface between DU and CU.
- X2 / Xn: 3GPP-specified. X2 originally was an interface between 4G eNBs, or eNBs and 5G NBs. This was to support multi-vendor RAN in non-standalone 5G, i.e., 5G RAN paired with 4G Core.[107]
- S1: 3GPP specified. Backhaul back to the core network.
- E2: O-RAN Alliance defined. Interface between the RAN Interface Controller (RIC) and the DU and CU, for the purpose of RAN optimization applications.[108]
- O1: O-RAN Alliance defined interface to Service Model Orchestration, enabling automation of RAN resource allocation.

These and other interfaces are described in the 5G Americas diagram in Figure 17. The diagram describes a network operator with both 4G (eNB, LTE) and 5G networks.

Recent reporting in the Wall Street Journal and other media indicates that recent cyber intrusions into US telecommunications networks may have exploited interfaces used for lawful intercept. "Lawful intercept" refers to law enforcement agencies with a warrant engaging in electronic surveillance of a person of interest.[109] Information on lawful intercept interfaces is provided by 3GPP, ETSI, Cisco and others, and typically involves use of the X1 or X2 interface defined by 3GPP.[110, 111]

106 O-RAN ALLIANCE Introduces 48 New Specifications Released Since July 2021. Accessed July 2024. https://www.o-ran.org/blog/o-ran-alliance-introduces-48-new-specifications-released-since-july-2021

107 Interviews indicate that relatively few network operators have mandated that equipment suppliers expose the X2 interface, which would enable multi-vendor, multigenerational RAN and minimize supplier lock-in. 5G Americas literature repeatedly provides NTT DOCOMO as an example.

108 How does 5G's O-RAN E2 interface work? 5G Technology World. Accessed July 2024. https://www.5gtechnologyworld.com/how-does-5gs-o-ran-e2-interface-work/

109 US wiretap systems targeted in China-linked hack. Wall Street Journal, September 2024, updated October 2024. https://www.wsj.com/tech/cybersecurity/u-s-wiretap-systems-targeted-in-china-linked-hack-327fc63b?st=igMZt9

110 ETSI, Lawful Interception (LI). https://www.etsi.org/technologies/lawful-interception#:~:text=As%20a%20legally%20sanctioned%20official,of%20private%20individuals%20or%20organizations

111 Lawful interception in mobile networks. 3GPP, updated August 2022. https://www.3gpp.org/technologies/li

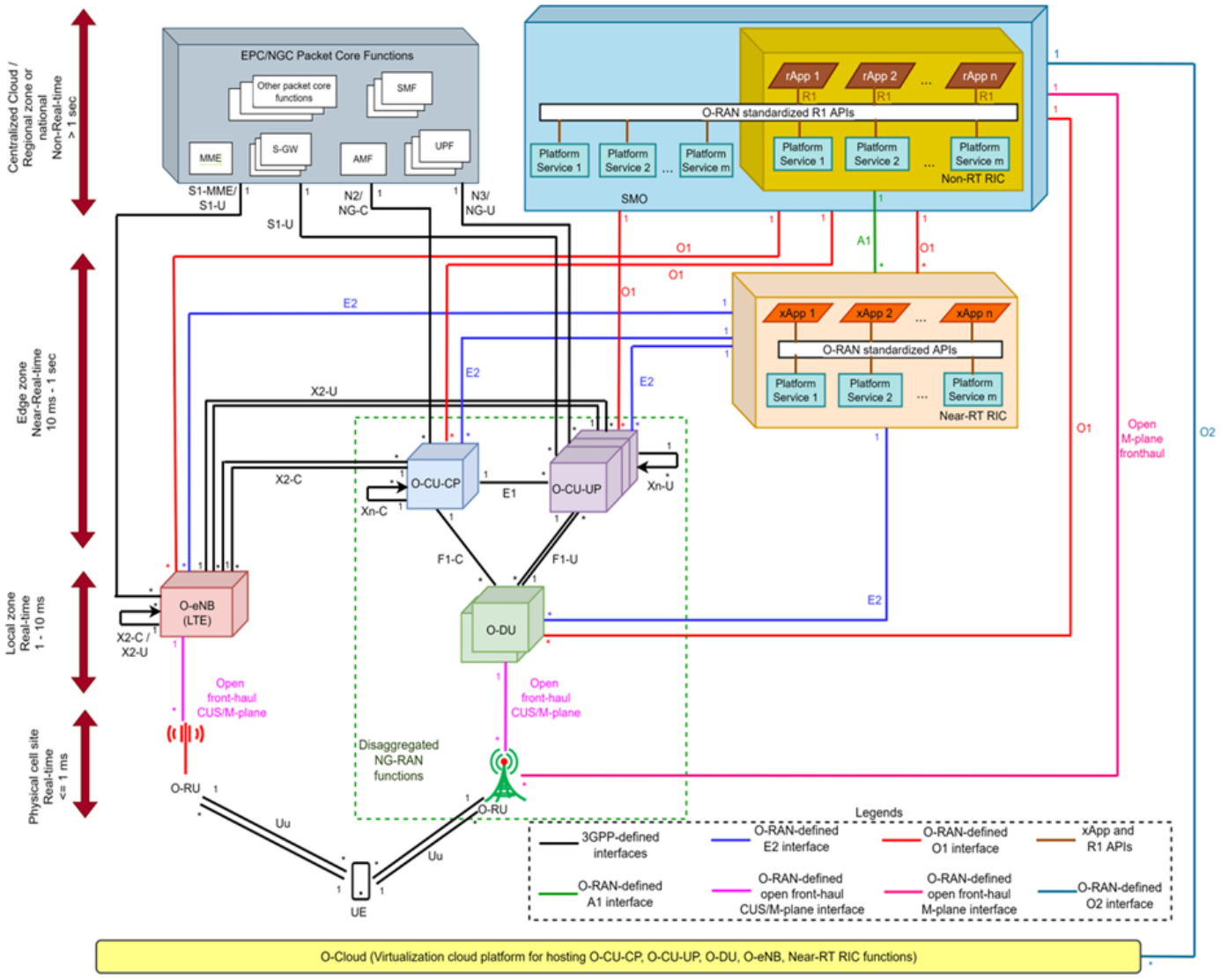


**Figure 17: 3GPP-defined and O-RAN network functions and interfaces. Source: 5G Americas, 2023**[112]

## WHAT CATALYZED OPEN RAN?

It is noteworthy, with the benefit of hindsight since the formation of TIP and the O-RAN Alliance, that different stakeholders in different parts of the world with different business agendas — from Meta to China Mobile to Rakuten — looked at the state of competition in the network equipment market, and at operator-supplier co-specialization, and independently arrived

112 5G Americas, The Evolution of Open RAN. Accessed July 2024. https://www.5gamericas.org/wp-content/uploads/2023/02/The-Evolution-of-Open-RAN-InDesign.pdf

at the same conclusion: that the advent of the cloud, and virtualization techniques, should be catalysts to drive efficiencies in RAN design and deployment; help facilitate supplier entry, particularly by players with skills honed in the enterprise IT and cloud market; and potentially lower the deployment costs for mobile networks, ultimately expanding the reach of wireless service.

Specifically, in founding TIP, Facebook (now Meta) looked at Open RAN as a way to lower the cost of mobile service; in founding the C-RAN Alliance, Chinese network operators looked at Open RAN as a way to hedge supplier (e.g. Huawei and ZTE) power; and in founding the X-RAN Forum, global network operators looked at Open RAN as a way to make the RAN software-definable. Similarly, enterprise IT suppliers, such as chip makers (e.g., Intel) or equipment makers (like Dell Technologies) saw a market that would likely share more similarities with the enterprise IT market, as did the hyperscalers (e.g., Amazon Web Services).

New entrants, such as Rakuten Mobile, also saw virtualization of the RAN as a way to deploy greenfield networks more quickly and with less expense. With Open RAN now at 5–10% revenue share in the total RAN market, depending on the quarter, we can say that Open RAN has been moderately impactful. Case studies like Rakuten Mobile have shown what is possible through the adoption of virtualization techniques in deploying networks. Going forward, we view that adoption by incumbent operators, and consistent support by policymakers, will be essential for Open RAN to truly lead to meaningful changes in RAN supplier diversity.

# Policymaker activity related to Open RAN

Having described what Open RAN is, what it unbundles, and why stakeholders from Meta to Chinese network operators had interest in unbundling the RAN, we now look at what geopolitical changes have meant for Open RAN, what Open RAN has meant within international alliance activity, and what that has meant for the market for Open RAN.

We start with legislative and executive activity in the United States. In the words of one interviewee, in a US national security context, Open RAN has come to mean "not Chinese" and also "a supplier other than Nokia and Ericsson." In other words, the US government for several years, across two different presidential administrations, has advocated to allied nations that they should remove equipment from Chinese suppliers from their networks. In engaging in that advocacy, the US government wants to be able to offer choices in addition to Nokia or Ericsson, a point made during multiple interviews with policymakers.

However, to prospective non-traditional suppliers aspiring to enter the market in the US or allied countries, in addition to meaning "not Chinese," Open RAN has come to mean "not in China either," which, as one supplier commented, reduces the overall addressable market for suppliers. From the perspective of inducing new suppliers to the market, this bears the risk of being counterproductive.

## US GOVERNMENT LEGISLATIVE AND EXECUTIVE ACTIVITY

US executive and legislative activity related to network equipment in the US market predates the advent of Open RAN as a term. For example, in 2007, Huawei and Bain Capital attempted to acquire 3Com. The deal did not go through due to security concerns. In 2011, CFIUS recommended that Huawei divest 3Leaf Systems, a US server technology company it had acquired in 2010.[113,114]

113 3Com to be acquired by Bain, Huawei for $2 billion: report. Reuters, September 2007. https://www.reuters.com/article/business/3com-to-be-acquired-by-bain-huawei-for-2-billion-report-idUSN28374688/

114 $2 million deal = Big CFIUS mistake. Troutman Pepper, March 2011. https://www.troutman.com/insights/2-million-deal-big-cfius-mistake.html

In response, in February 2011, Huawei issued an open letter to the US government inviting investigation into it. In 2011, the Permanent Select Committee on Intelligence in the US House of Representatives responded to that invitation with an investigation of Chinese network equipment suppliers in the United States. The Committee issued its report in October 2012, after inviting representatives of Huawei and ZTE to testify before the Committee in September 2012.[115,116]

In 2013, 70% of Sprint Nextel (now part of T-Mobile) was acquired by Japan's SoftBank. One of the conditions of that acquisition was that Sprint not deploy Huawei, and that it remove any equipment from Huawei or other Chinese suppliers from its network. Sprint had previously acquired Clearwire, which had sourced from Huawei as a supplier, and one of the conditions of that acquisition was that Huawei equipment be removed.

Since 2018, the United States Congress has passed a variety of legislation related to communications and communications infrastructure. The executive branch has also issued multiple executive orders directing various executive agency and departmental activity. In parallel, the US government has engaged in international advocacy. Notably, in May 2019, government officials from the United States and 30 other countries, along with representatives from the European Union and NATO, gathered in the Czech Republic for the first Prague 5G Security Conference. Recommendations from this initial conference are referred to as the Prague Proposals.[117,118] This led to subsequent advocacy for "clean networks."

Below, we have listed in chronological order executive and legislative activity in the United States related to communications and communications infrastructure.

- December 2018: The Federal Acquisition Supply Chain Security Act.[119] This established a Federal Acquisition Security Council and provided executive agencies with authorities related to mitigating supply chain risks in the procurement of information technology.
- May 2019: Executive Order Securing the Information and Communications Technology and Services Supply Chain.[120] This declared a national emergency due to risk of exploitation via vulnerabilities in information and communications technology and services, and

115 https://intelligence.house.gov/news/documentsingle.aspx?DocumentID=327
116 https://stacks.stanford.edu/file/druid:rm226yb7473/Huawei-ZTE%20Investigative%20Report%20(FINAL).pdf
117 https://cz.usembassy.gov/the-united-states-applauds-the-czech-republic-for-hosting-the-prague-5g-security-conference/
118 https://nukib.gov.cz/download/5G_site/Prague_Proposals_ENG.pdf
119 https://www.congress.gov/bill/115th-congress/senate-bill/3085/text
120 https://trumpwhitehouse.archives.gov/presidential-actions/executive-order-securing-information-communications-technology-services-supply-chain/

empowered the Secretary of Commerce, in consultation with other cabinet secretaries, USTR, DNI, and the FCC chair, to take actions related to mitigation of this risk.

- March 2020: The Secure and Trusted Communications Network Act of 2019.[121] This directed the FCC to create a Supply Chain Reimbursement Program, allocating $1.9 billion to fund rip-and-replace activity by largely rural carriers to remove Huawei and ZTE equipment from their networks.
- March 2020: The Secure 5G and Beyond Act of 2020. This directed the President and relevant federal agencies to develop a strategy to secure and protect United States 5G and future generation systems and infrastructure.[122]
- April 2020: The State Department announced it would require a "clean path" for all 5G network traffic to and from US diplomatic facilities.[123]
- October 2020: The Federal Communications Commission adopted a Report & Order establishing the 5G Fund for Rural America, which made up to $9 billion available to bring 5G mobile broadband to rural areas.[124]
- January 2021: CISA issued its CISA 5G Strategy; NTIA issued its Secure 5G and implementation plan. [125, 126]
- June 2021: Executive Order on Protecting Americans' Sensitive Data from Foreign Adversaries. This superseded the May 2019 Executive Order. [127]
- June 2021: FCC Report and Order increased eligibility for the Secure and Trusted Networks Reimbursement Program. This expanded the scope of eligibility for funding for rip-and-replace activity from service providers with fewer than two million subscribers to those with up to 10 million subscribers. Funding for this was provided to FCC through the 2021 Consolidated Appropriations Act. [128]
- November 2021: The Infrastructure Investment and Jobs Act, among other provisions, provided grant funding for broadband connectivity, digital equity, middle-mile broadband infrastructure, and broadband affordability, and also included funding for telecommunications workforce development.[129] This led to NTIA administering six funding programs for broadband promotion, including $42.5B for the Broadband Equity Access and Deployment (BEAD) program.

121 https://www.congress.gov/bill/116th-congress/house-bill/4998
122 https://www.congress.gov/bill/116th-congress/senate-bill/893
123 https://2017-2021.state.gov/building-a-clean-network-key-milestones/
124 https://www.fcc.gov/5g-fund
125 https://www.cisa.gov/resources-tools/resources/5g-strategy
126 https://www.ntia.gov/other-publication/national-strategy-secure-5g-implementation-plan
127 https://www.whitehouse.gov/briefing-room/presidential-actions/2021/06/09/executive-order-on-protecting-americans-sensitive-data-from-foreign-adversaries/
128 https://docs.fcc.gov/public/attachments/DOC-373481A1.pdf
129 https://www.congress.gov/bill/117th-congress/house-bill/3684

- August 2022: The CHIPS and Science Act of 2022.[130] Among other provisions, this provided $1.5 billion in funding for the Public Wireless Supply Chain Innovation Fund, to be administered by NTIA. It also provided $500 million ($100M per year over five years) in funding to the Department of State as the Information Technology Security and Innovation Fund.[131]
- September 2023: FCC, having completed the process of measuring and mapping broadband availability in the US, issued a further Notice of Proposed Rulemaking on methodology for how to administer the funding allocated in the 5G Fund Report and Order of 2020.
- August 2024: FCC issued a Report and Order (in the Matter of Establishing a 5G Fund for Rural America), including an additional $900 million in potential support for Open RAN deployments in conjunction with the $9 billion Rural 5G Fund, and the ability for network operators to seek limited extensions in their 5G deployment milestones, if deploying Open RAN necessitates additional time.[132]

Looking back, it is noteworthy that this sequence of activity focused on communications infrastructure has straddled multiple presidential administrations in the United States. The issue of communications infrastructure and which companies provide it has been greatly elevated as an area of attention. The US government has put forth various sources of funding, such as funds for rip-and-replace activities, or for nurturing new suppliers, such as funding opportunities, administered by NTIA, created by the CHIPS and Science Act.

With that said, US network operators had largely made their 5G supplier decisions prior to this flurry of legislative and executive activity, and so the increased attention on Open RAN has not yet led to substantive changes in what companies provide network equipment in the United States. Rather, Samsung and Ericsson have both gained some share at Nokia's expense; Samsung with Verizon, and Ericsson, through "single vendor Open RAN" at AT&T. DISH, a new entrant in the US market harnessing Open RAN techniques, still has a limited service footprint.[133]

130 https://www.congress.gov/bill/117th-congress/house-bill/4346

131 https://www.state.gov/the-u-s-department-of-state-international-technology-security-and-innovation-fund/

132 FCC Report and Order, August 2024. https://docs.fcc.gov/public/attachments/FCC-24-89A1.pdf

133 Dish seeks more time for 5G buildout, Light Reading, September 2024. https://www.lightreading.com/regulatory-politics/dish-asks-fcc-for-more-time-for-5g-buildout

## OPEN RAN POLICY COALITION AND RAKUTEN MOBILE ADVOCACY

In the United States, network operators led by AT&T created the Open RAN Policy Coalition in May 2020.[134, 135] Diane Rinaldo, who previously served as acting NTIA administrator, joined as Executive Director.[136] The coalition has an executive committee comprising representatives of AT&T, Cisco, Qualcomm, and Verizon; and a board of directors that also includes representatives of DISH, Facebook, Fujitsu, Intel, Mavenir, NTT, Rakuten Symphony, Samsung Electronics America, VMware, and Vodafone Group.[137] While based in the US, the Coalition engages in both domestic and international advocacy; as of March 2024, the Coalition claimed it had global engagement in over 80 countries.[138] Notably, the Coalition has worked since 2021 to coordinate efforts between members of the Quadrilateral Security Dialogue (i.e., the Quad, comprising Australia, India, Japan, and the United States), and the Global Coalition on Telecommunications (GCOT, comprising Australia, Canada, Japan, the United Kingdom, and the United States), which was formed in October 2023.[139]

The Coalition has found a receptive audience in the United States. Various arms of the US Government have taken a keen interest in Open RAN. It is the stated position of multiple representatives of the US security and intelligence communities spoken with for this report that the absence of a US network equipment champion (e.g., the former Lucent, now part of Nokia Networks) has left the US underrepresented in global standards-setting organizations like 3GPP.[140] A second reason, cited during various interviews, is the recognition that if the US Government is going to request that allies not purchase from Huawei or ZTE (and if Huawei and ZTE equipment is already deployed, that that equipment be removed), then it should be able to offer alternatives in addition to traditional suppliers such as Ericsson and Nokia.

134 Open RAN Policy Coalition launches. RCR Wireless, May 2020. https://www.rcrwireless.com/20200505/5g/open-ran-policy-coalition-launches

135 It is worth noting that the Coalition was formed about four months after then-AG Bill Barr publicly spoke about potentially nationalizing a RAN supplier, and one month after Congress passed the Secure 5G and Beyond Act of 2020. https://www.congress.gov/bill/116th-congress/senate-bill/893

136 https://www.openranpolicy.org/about-us/board-and-executive-committee/

137 Full membership at formation included: Airspan, Altiostar, AWS, AT&T, Cisco, CommScope, Dell, DISH Network, Facebook, Fujitsu, Google, IBM, Intel, Juniper Networks, Mavenir, Microsoft, NEC Corporation, NewEdge Signal Solutions, NTT, Oracle, Parallel Wireless, Qualcomm, Rakuten, Samsung Electronics America, Telefónica, US Ignite, Verizon, VMWare, Vodafone, World Wide Technology, and XCOM-Labs.

138 See Diane Rinaldo testimony to Senate Commerce committee, March 2024. https://www.commerce.senate.gov/services/files/AF5318D7-7F73-4570-AACC-02AA8F055BB3

139 https://www.ntia.gov/press-release/2023/statement-assistant-secretary-davidson-global-coalition-telecommunications

140 This comment was echoed in multiple conversations with current and former US government officials, both in public forums (e.g., the RSA Security Conference) and in private.

In that context, the message that various representatives of Rakuten Mobile (both from Japan and from Rakuten Mobile's US entity) have conveyed in Washington is that there is another, more cost-effective and agile way to build a wireless network — and one that uses US suppliers (at the time, Altiostar, now part of Rakuten Symphony, and Intel). This message seems to have landed on receptive ears both before and after the passage of the CHIPS and Science Act (CHIPS Act) of 2022. [141, 142, 143, 144]

## CHIPS AND SCIENCE ACT OF 2022

Passed in August 2022, the CHIPS Act allocated $1.5 billion over 10 years toward a Public Wireless Supply Chain Innovation Fund, administered by the National Telecommunications and Information Association.[145] Initial funding opportunities were divided into two categories:

- Round 1 (2023): Research and Development, Testing and Evaluation (total funding of up to $140.5M).
- Round 2 (2024): Open RU (total funding of up to $420M).

The deadline for Round 2 was July 17, 2024. Roughly two-thirds of Round 1 funds were allocated for two test and engineering centers, one administered by DISH, and one administered by AT&T.[146] In total, $144.443M in funding went to 17 recipients from industry and academia.[147]

Round 2 funds will be allocated between two specific research focus areas (SRFA):[148]

141 https://www.lightreading.com/open-ran/open-ran-vendors-get-another-helping-hand-from-us-regulators

142 Example: then Rakuten CTO Tareq Amin testifies to House Commerce Committee. April 2021. https://democrats-energycommerce.house.gov/sites/evo-subsites/democrats-energycommerce.house.gov/files/documents/Witness_Testimony_Amin_CAT_2021.04.21.pdf

143 Rakuten ex parte notice of meeting with FCC Chair Jessica Rosenworcel, May 2024. https://www.fcc.gov/ecfs/document/1052952759155/1

144 Floundering in open RAN, the US sniffs around Rakuten, Light Reading, May 2024. https://www.lightreading.com/open-ran/floundering-in-open-ran-the-us-sniffs-around-rakuten

145 https://www.ntia.gov/program/innovation-fund

146 https://www.ntia.gov/program/innovation-fund/grant-programs/round-1-2023/award-recipients

147 Round 1 recipients included: AT&T Corp ($42.3M); Booz Allen Hamilton ($1.99M); Cirrus360 ($1.99M); DeepSig ($1.42M); DISH Wireless ($50M); Michigan State University ($1.73M); Mississippi State University ($1.32M); New York University ($2M); Northeastern University ($1.997M, $1.999M, $1.99M); Open Networking Foundation (with Rutgers University; $1.96M); PhasorLab (with Parallel Wireless and Cimulate; $1.999M); Rice University ($1.94M); Viavi Solutions ($21.71M); Virginia Polytechnic Institute and State University ($2.0M, $2.0M). Further details at: https://www.ntia.gov/program/innovation-fund/grant-programs/round-1-2023/award-recipients

148 https://www.ntia.gov/funding-programs/public-wireless-supply-chain-innovation-fund/round-2-2024-open-ru

- SRFA1: Open Radio Unit (RU) Commercialization (available funds: $25M–$45M per project). Proponents must be capable of production and commercial sale of Open RUs and be in partnership with one mobile network operator. Period of performance: 18–24 months
- SRFA2: Open RU Innovation (available funds: $5M–$10M per project). Seeks proposals with targeted research and development to improve the performance of RUs. Period of performance: 3–5 years.

Bidders noted that the NTIA solicitation was thoughtfully designed to generate a multiplier effect, and that for smaller network operators, the funds were sufficient to offset the cost of hiring staff with RU expertise.[149]

## COMMENTARY ON US EXECUTIVE AND LEGISLATIVE ACTIVITY

The cadence of legislative, executive, and executive agency activity straddles Republican and Democratic administrations. Timelining this activity provides multiple insights:

- The issue of secure communications infrastructure has seen consistent bipartisan support.
- Executive agencies such as NTIA and CISA were working up to the final days of the transition of administrations in January 2021 and again in January 2025.
- NTIA has needed to scale up as an agency to handle the volume of activity assigned to it.[150]
- Executive agency leadership appointments have lagged.
    - The FCC did not have a full allotment of commissioners until September 2023.[151]
    - NTIA Administrator Alan Davidson took his position in January 2022, one year after the transition in administrations.[152]
- Implementation and spending by executive agencies has lagged.
    - The FCC has not allocated the $9B in 5G funding allocated to it (5G Fund for Rural Americas), opting to first complete broadband measurement and mapping. In August 2024, the FCC issued a new report and order for the Rural 5G Fund, and

149 NTIA announced award recipients for its Round 2 solicitations in December 2024 and January 2025. https://www.ntia.gov/press-release/2024/biden-harris-administration-awards-273-million-wireless-innovation

150 In NTIA's 2022 year in review, NTIA Administrator Alan Davidson notes that 1/3 of NTIA were newly hired from when he took the role in January 2022.

151 Senate confirms Anna Gomez to FCC, breaking yearslong deadlock at the agency, CNBC, September 2023. https://www.cnbc.com/2023/09/07/senate-confirms-anna-gomez-to-fcc-breaking-years-long-agency-deadlock.html

152 https://www.ntia.gov/press-release/2022/ntia-announces-additions-senior-leadership-under-assistant-secretary-davidson

one that offers potential additional incentives for adoption of Open RAN. But these funds remain unallocated.

- The FCC's spectrum auction authority lapsed in March 2023.
- The Affordable Connectivity Fund, which provided discounted broadband access to 23 million households, ran out of funding in June 2024.[153]
- Rip-and-replace funding has been insufficient relative to network operator requests submitted to the FCC, leaving a funding gap of close to $3 billion.[154]
- BEAD plans for the 50 states were only completed in November 2024, three years after BEAD funding was created in the Infrastructure Investment and Jobs Act in 2021.

The consistent cadence of activity is laudable. Yet, the emphasis on locally administered grants directs funding toward point solutions for point problems, and leaves questions on whether the broader question of more diverse RAN suppliers and more robust connectivity for citizens will go unsolved.[155] Recent history highlights the shortcomings of grant programs with the goal of furthering broadband access. The US government allocated $7.2 billion toward broadband grants as part of the American Reinvestment and Recovery Act of 2009. These were administered by NTIA and the Rural Utilities Service. Yet when the Covid-19 pandemic forced remote work and remote education, it highlighted woeful shortcomings in broadband availability. Clearly, the patchwork of NTIA BTOP and RUS grants funded by the ARRA stimulus had not solved the broader issue of providing reliable broadband access across the country.[156]

Highlighting one example from Round 1 of the NTIA grants from the Public Wireless Supply Chain Innovation Fund, DISH, a greenfield 5G carrier that has adopted Open RAN, received $50 million from NTIA to create an Open RAN test and engineering center.[157] Whether DISH itself can deliver 5G service at national scale is still in question. Will $50 million from NTIA help DISH become a viable competitive entrant in the 5G market? Most likely not — the capital requirements for national wireless service are in the tens of billions, factoring in infrastructure, spectrum, and handset acquisition costs. Conversely, $50 million in funding could meaningfully change the trajectory of a startup RAN supplier, helping them traverse the "valley of death" between proof-of-concept and commercialization at scale. Further, recurring, predictable funding opportunities each year could

153 FCC: Affordable Connectivity Program has ended- frequently asked questions. June 2024. https://www.fcc.gov/sites/default/files/ACP-FAQs-Post-ACP-Ending.pdf

154 US carriers to get 39% of what they want for FCC's 'rip and replace', Light Reading, July 2022. https://www.lightreading.com/security/us-carriers-to-get-39-of-what-they-want-for-fcc-s-rip-and-replace-; FCC announcement, WC docket 18-39: https://docs.fcc.gov/public/attachments/DA-22-774A1.pdf

155 https://www2.ntia.doc.gov/about

156 https://www.politico.com/story/2015/07/broadband-coverage-rural-area-fund-mishandled-120601

157 In fairness, AT&T also received funding to develop an Open RAN testing center. Our intent is not to pick on DISH. Rather, our goal is to highlight where government funding can have the most impact.

induce more new startup RAN suppliers to enter the RAN market, and induce network operators to develop their own integration capabilities to work with these new suppliers. These capabilities have withered with the co-dependence with key network suppliers.

We also note that the funding that has been allocated to the FCC (e.g., $9 billion for the Rural 5G Fund) and NTIA (e.g., $42.5 billion for the BEAD program) would be more than sufficient to stand up a new national greenfield Open RAN 5G carrier, or at least, a greenfield carrier focused solely on underserved rural markets. We are not necessarily advocating this option, but rather, point this out to emphasize that more targeted, concentrated allocation of funding could lead to more broadly impactful solutions.

## OPEN RAN AND INTERNATIONAL ALLIANCE ACTIVITY

International alliance activity by the US government spanning multiple presidential administrations was a catalyst for this report. One example, previously highlighted in this report, was the inaugural Prague 5G Security Conference, held in 2019. This has continued and is now known as the Prague Cyber Security Conference.[158] The Prague Proposals on Telecommunications Supplier Diversity put forward following the initial Prague 5G Security Conference were subsequently adopted by the G7.[159]

In a second example, in May 2023, the National Telecommunications and Information Association (NTIA) published an Open RAN Security Report. This was published in advance of a meeting of the leaders of the Quadrilateral Security Dialogue, composed of Australia, India, Japan and the United States.[160] The report was a product of the Quad's Critical and Emerging Technology Working Group, and assessed risks of Open RAN versus those of traditional RAN. The report also integrated prior assessments, such as those given by CISA, in the US; NTT DOCOMO, in Japan; and IFRI, in France.

NTIA's paper found that the use of Open RAN networks "does not fundamentally alter the security risk landscape for telecommunications, compared to more traditional RAN." All told, Quad's Critical and Emerging Technology Working Group found 55 risks, or 4% of a total of 1375, that were unique to Open RAN, whereas the remaining 1320 were risks also common to traditional RAN deployments.

158 https://www.praguecybersecurityconference.com/about/

159 https://nukib.gov.cz/download/OFFICIAL_Prague_Proposals_on_Telecommunications_Supplier_Diversity.pdf

160 Interest by the Quad member countries in Open RAN was one catalyst for this paper. NTIA, Open RAN Security Report, May 2023. https://www.ntia.gov/report/2023/open-ran-security-report

## Outline of the Quad Open RAN Security Report

- As a response to the growing interest in the security of Open RAN, this 160-page report analyzes **the advantages, challenges and possibilities of overcoming challenges of Open RAN** compared to traditional RAN through **objective research and analysis including technical demonstration**.
- Released as one of the outcomes of the Quad on May 2023, based on the "Memorandum of Cooperation on 5G Supplier Diversification and Open RAN" of the **Quad Critical and Emerging Technology Working Group**.

<Advantages, challenges and possibilities of overcoming challenges of Open RAN>

| | | |
|---|---|---|
| **Advantages** | Security | **Easier risk management** due to improved transparency, etc. |
| | Others | **Reduction of supply chain risk and avoidance of vendor lock-in** due to reduced dependence on specific suppliers, etc. |
| **Challenges** | **Approximately 4% of security risks analyzed in this report are unique to Open RAN** (i.e., not also present in traditional RAN), based on inclusion of new interfaces/components. | |
| **Possibilities of overcoming challenges** | Possible to **reduce risks** unique to Open RAN and achieve **security level equivalent to traditional RAN**, by meeting the security requirement in standards and **the checklist attached to this report**.<br>Note: Security of Open RAN can be further enhanced by activating optional security procedures. | |


Cover of the report which was published as an outcome of Quad

**Use of Open RAN does not fundamentally alter the security risk landscape for telecommunications, compared to traditional RAN**, given the objective analysis as above of the advantages, challenges and possibilities of overcoming challenges.

**Figure 18: Quad Open RAN Security Report: Summary of findings**[161]

We address the Quad's report, and comment on security risks unique to Open RAN relative to traditional RAN, in the following section.

In May 2023, the US Agency for International Development (USAID) announced $135M in support, subject to Congressional approval, for the Philippines, a portion of which would be allocated toward an Open RAN Interoperability Lab to support the upcoming rollout of 5G in the Philippines.[162] In addition, Open RAN was on the agenda during the trilateral summit between the United States, Japan, and the Philippines in April 2024.[163] Media reporting indicates the the Biden Administration, and President Biden himself, raised the subject of Open RAN during meetings with heads of state from India, Saudi Arabia, Brazil, Palau, Indonesia, and the Philippines, among others.[164]

161 Accessed at https://www.ntia.gov/report/2023/open-ran-security-report

162 US, Philippines step closer to launching first Open RAN laboratory in Manila, US Embassy Manila, Philippines, June 2024. https://ph.usembassy.gov/united-states-philippines-step-closer-to-launching-first-open-ran-laboratory-in-manila/

163 Joint Vision Statement from the Leaders of Japan, the Philippines, and the United States. https://www.whitehouse.gov/briefing-room/statements-releases/2024/04/11/joint-vision-statement-from-the-leaders-of-japan-the-philippines-and-the-united-states/

164 Trump dreamt of a 'Huawei killer.' Biden is trying to unleash it. Washington Post, February 2024. https://www.washingtonpost.com/technology/2024/02/12/oran-biden-china-huawei-technology/

The USG's embrace of Open RAN in international alliance activity has had results. NSC staff, in public remarks at the RSA Security Conference in April 2024, cited Costa Rica as a public success case. (NSC staff, in interviews for this report, commented that at any one time, there may be 50 network tenders happening worldwide, and its goal for Open RAN is to nurture increased choice within those tenders.) State Department ITSI funds have been allocated toward workforce development to develop semiconductor assembly, testing, and packaging capabilities.[165]

The Philippines appears to be another potential alliance success, and one that comes in partnership with US allies such as Japan.[166] With that said, there have been critics of the US government's embrace of Open RAN in alliance-building activity, claiming the US government has co-opted what had originally been a more global movement.[167,168] Chinese members of the original O-RAN Alliance (which includes members of the C-RAN Alliance, founded in China in 2016 to nurture alternatives to domestic suppliers such as Huawei) have also commented on being disenfranchised from a movement they helped found. Multiple Open RAN suppliers also commented that the loss of access to the Chinese market has reduced the overall market opportunity for Open RAN.

165 U.S. CHIPS Act funds to support semiconductor workforce development in Costa Rica, US Embassy San Jose, Costa Rica, February 2024. https://cr.usembassy.gov/u-s-chips-act-funds-to-support-semiconductor-workforce-development-in-costa-rica/

166 Trump dreamt of a 'Huawei killer.' Biden is trying to unleash it. Washington Post, February 2024. https://www.washingtonpost.com/technology/2024/02/12/oran-biden-china-huawei-technology/

167 https://www.lightreading.com/5g/the-political-hijacking-of-open-ran

168 https://www.researchgate.net/publication/350875082_The_political_hijacking_of_open_networking_The_case_of_open_radio_access_network

# Security risks unique to Open RAN

Open RAN involves standardizing and publishing interfaces between different elements in the RAN, with the goal of facilitating hardware and software diversity and interoperability. One goal in creating the Open RAN Alliance, as discussed earlier, was to more clearly define these interfaces, with more detail than 3GPP traditionally had. Further, Open RAN can involve putting some elements of the RAN, such as the CU or DU, into the cloud. Does more clearly defining interfaces between RAN elements, or putting elements of the RAN into the cloud, create any new risks, and how do those compare with risks already inherent to traditional RAN implementations?

To an extent, this is a similar debate to when enterprises were first assessing use of cloud services and comparing them with traditional on-premise hardware and software. The cloud offers potentially increased operational resilience and flexibility, but centralizing resources in the cloud may create new vulnerabilities, or create honeypots attractive to potential attackers.

The Quad's Critical and Emerging Technology Working Group assessed Open RAN from the perspective of whether Open RAN was additive relative to traditional monolithic RAN. Conducting this assessment necessitated certain assumptions about how network operators would secure network traffic and whether they would use public cloud services if putting RAN elements in the cloud. For example, the working group assumed the CU would be deployed in a public cloud. Security assumptions made by the working group are summarized in Figure 19 below.

The working group followed the STRIDE (Spoofing, Tampering, Repudiation, Information disclosure, Denial of service, Elevation of privilege) framework to identify various security threats, and then weighted potential threats by the combination of potential impact and likelihood of occurrence. The working group built on previous analyses, such as that by CISA in September 2022.[169] The Quad's working group found that most of the potential security threats from Open RAN (a total of 1338) were shared with traditional RAN, and 55 were unique to Open RAN. For example, if an Open RAN network operator deployed an O-Cloud on a public cloud, any risks from that would be unique to Open RAN relative to traditional RAN. The assessment did not

169 Open Radio Access Network Security Considerations, jointly published by the NSA, CISA, ITSCC, CSCC, and DIB Sector Coordinating Council, September 2022. https://www.cisa.gov/sites/default/files/publications/open-radio-access-network-security-considerations_508.pdf

| Domain | Assumption |
|---|---|
| 3GPP User Plane | - AS Encryption: Assumed to be turned on<br>- AS Integrity: Assumed to be turned off<br>- Backhaul (NG-U, NG-C) security: Assumed to be turned off |
| 3GPP Control Plane | - NAS Encryption: Assumed to be turned on<br>- NAS Integrity: Assumed to be turned on<br>- SUCI: Assumed to be plain text SUPI<br>- IMSI paging: Assumed to not be used<br>- GUTI: Assumed to be rotated |
| O-Cloud | - O-CUs are assumed to be deployed on a public cloud |
| Physical security | - O-RUs are not physically secure<br>- O-DUs are deployed in shared facilities<br>- O-CUs are deployed in a shared data center |

**Figure 19: Security assumptions made by the Quad's Critical and Emerging Technology Working Group in assessing security risks of Open RAN deployments relative to traditional RAN**[170]

assess risks outside of NG-RAN (5G-only), i.e., risks inherited when deploying 5G RAN with 4G Core. As previously noted, many 5G operators in practice will pair 5G RAN with 4G Core.

A total of 10 components and interfaces (i.e., O-Cloud, R1, Non-RT RIC, rApp, A1, SMO, O2, O1, E2, and OFH M) were assessed to map to the most high-risk threats.[171] In particular, the O-Cloud was assessed as the component linked to the most high-rated risks, due its role as enabling infrastructure that provides cloud computing capabilities to host various RAN network functions. The authors noted that virtualization of the RAN, even if not "open" (unbundled across different suppliers), would bear the same risk to the extent that the RAN equipment provider virtualized elements of the RAN. Thus, O-Cloud, O-CU, and O-DU interfaces were not considered unique to Open RAN, as Cloud RAN or vRAN would bear the same risks. Still, the authors assessed that the O-Cloud introduced a new potential single point of failure that did not exist with traditional RAN deployments. The O-Cloud and other elements are shown in Figure 20 below.

170 Figure 19 appears as Table 4 on page 14 of the Open RAN Security Report, May 2023. https://www.ntia.gov/report/2023/open-ran-security-report

171 Page 33–34, Open RAN Security Report, May 2023.

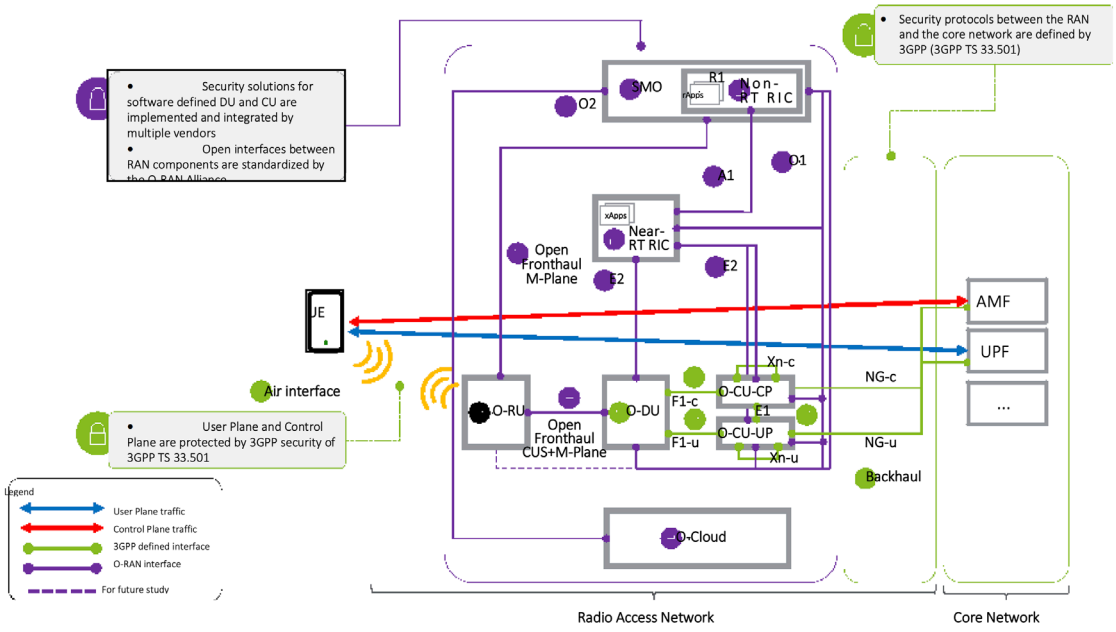


**Figure 20: High-level architecture diagram of Open RAN deployments. Interfaces color-coded by whether they are defined by 3GPP or the O-RAN Alliance. Appears as Figure 1 in Quad working group report.**[172]

The report assessed that more open interfaces would be a net benefit to network operators, as it would allow more independent testing and verification of network equipment, rather than trusting the testing of proprietary interfaces by traditional vendors.[173] The authors also noted that standardizing interfaces could help mitigate supply chain risk, such as in the scenario that access to equipment from a specific supplier is interrupted for some reason.

We note that recent intrusions into US telecommunications networks may have exploited interfaces used for lawful intercept. If so, these interfaces are longstanding 3GPP-specified interfaces, and are not risks created by Open RAN.

172 Appears as Figure 1 on page 11 of Open RAN Security Report, May 2023.

173 We note here philosophical similarities between this debate and that which used to characterize open source software, and between that regarding on-premise software and the cloud. Open source software advocates consistently noted that having "more eyes" looking at software made it more likely that flaws would be detected and fixed. Similarly, with the debate between on-premise hosting of software and hosting software on the cloud, the cloud came to be seen as offering more operational resilience.

# Has Open RAN meaningfully impacted supplier diversity?

Have movements to unbundle the RAN, including the various efforts by the US government and other governments, led to increased RAN supplier diversity? Based on RAN market revenue share, the answer is no, not yet. Globally, the combined share of the top 5 RAN suppliers is still around 95%, albeit with some redistribution among them, as Samsung has gained share. Greenfield Open RAN networks, such as Rakuten Mobile's in Japan, led to Open RAN reaching an estimated 5–10% of total RAN spend during the buildout phase, but that buildout is largely complete.

In the US case, this is partly because network operators have consolidated into a "big three," and they have largely made their 5G supplier decisions already. Further, AT&T's Open RAN announcement in December 2023 had the net effect of further solidifying Ericsson's position as a prime equipment supplier and integrator partner for much of its network.

More structurally, the relative lack of change in network equipment supplier diversity is due to the nature of the mobile infrastructure market. Entering the mobile infrastructure market as a new supplier requires successfully navigating three timelines.

- Network generation upgrade cycle: e.g., 3G to 4G, 4G to 5G. This typically occurs once per decade, with mid-cycle incremental upgrades (e.g., 3.5G, 4.5G, etc.) occurring in between generational upgrades.
- Wireless infrastructure startup maturation cycle: 5–7 years at the minimum, often longer.
- Network operator evaluation cycle for network equipment suppliers: 18–24 months.

There are startup entrants that do indeed successfully navigate these timelines, and generate venture-scale returns based on successful deployment with mobile network operators. Flarion, acquired by Qualcomm in 2005, is one example; more recently, Altiostar, acquired by Rakuten in 2021, is another.

GSMA tracks data on 1250 network operators in 195 countries. In an interview in summer 2023, NSC staff estimated there were 50 5G tenders — solicitations from network operators as they plan their 5G network rollouts — happening worldwide. Mobile infrastructure is a global market, but within a given country, customers are concentrated, with a typical "Rule of 3" visible

in most markets. In addition, as described earlier, network operators often assign key network equipment suppliers to act as prime suppliers in a given territory. Thus, new entrants, even if they weather network operator evaluation cycles and ultimately get to adoption, still need to integrate with incumbent prime suppliers who may be reluctant to work with them. Breaking through this reluctance requires mandates from operators themselves, who are ultimately the customers.

Thus, getting to commercial scale as a new infrastructure startup requires the ability to weather long evaluation cycles, navigate concentrated buyers, and co-exist with incumbent network suppliers that may act to protect their customer positions. Successfully scaling a startup targeting network operators therefore takes not only technology, but also patient funding and the ability to navigate these timelines. Therefore, adding diversity to the RAN supplier market will take years. It will take commitment from policymakers to keep diversification of the RAN market as a priority, and it will also take commitment from network operators. If policymakers, perhaps when planning spectrum tenders, truly want to shape network operator evaluation criteria in a way that will make Open RAN from non-traditional suppliers a priority, they will need to assess use of carrots (incentives), sticks (disincentives), or both.

Currently, established network operators will say they are waiting for newer Open RAN suppliers to reach "feature parity" with incumbent suppliers. This elicits the question: just how important is it for new suppliers to support features from the 2G and 3G eras? And for how long must they maintain this support? The relative speed of Rakuten Mobile's deployment, described below, of a 4G/5G greenfield national network shows what is possible if designing a network that does not require legacy 2G/3G feature support. Network modernization, such as moving to standalone 5G, also has security benefits, such as those articulated by T-Mobile US in response to recent intrusions (Salt Typhoon) into US communications networks.[174]

The share of the total RAN market that Open RAN has gained (between 5–10% of total, depending on the quarter, though lower now that greenfield operators have largely completed network buildouts) has come in part from greenfield operators such as Rakuten, 1&1, and DISH. As one interviewee commented, dramatic change in the mobile industry comes through entrepreneurs. That said, due to market maturity and the capital requirements involved, entrepreneur-founded, facilities-based mobile network operators are unusual these days, unlike in the earlier formative days of wireless, when carriers were often regional and more entrepreneurial in nature. Qualcomm's adoption by PacTel Cellular in 1990 was an example of

174 An update on recent cyber attacks targeting US wireless companies; T-Mobile, November 2024. https://www.t-mobile.com/news/un-carrier/update-cyberattacks-targeting-us-wireless-companies

the power of reference customers in promoting new technology standards. With that said, PacTel has been subsumed into AirTouch, which is now part of Verizon in the US. There are still opportunities with smaller, regional carriers in the US, but carriers that are startups themselves are few and far between.

On the topic of startup carriers, next we look at one greenfield carrier, Rakuten Mobile, which, as of November 2024, served eight million customers in Japan. Rakuten Mobile entered a market that was already well-served, with price and network competition between three major national operators, NTT DOCOMO, KDDI, and SoftBank Mobile. Rakuten's example encapsulates multiple insights relevant to greenfield and brownfield operators, policymakers, and RAN suppliers.

# Rakuten Mobile

Rakuten Mobile initially launched mobile service in Japan as an MVNO on operator partner NTT DOCOMO's network. Rakuten Mobile is owned and funded by Rakuten Group (TSE: 4755), a leading e-commerce and fintech services provider that primarily conducts business in Japan. Rakuten announced plans to launch its own facilities-based mobile network operator in Japan in 2017.[175] This service opened to customer applications in fall 2019, and launched in April 2020.[176, 177]

As of fall 2023, Rakuten Mobile had over 60,000 base stations providing 4G and above service in 98.8% of Japan's territory. Rakuten Mobile is thus the unusual 4G-and-above national greenfield carrier, along with Reliance Jio of India. And indeed, Rakuten Mobile hired its founding network architect, Tareq Amin, from Reliance Jio.[178] Thus, Rakuten Mobile and Reliance Jio share the following attributes:

- 4G-and-above greenfield national network operators;
- Founded by wealthy entrepreneurs (Mukesh Ambani for Reliance Jio, and Hiroshi Mikitani for Rakuten Mobile); and
- Originally architected by Tareq Amin, now CEO of Aramco Digital.

Being greenfield 4G-and-above meant that both Reliance Jio and Rakuten Mobile did not have to design networks that co-exist with prior generations of network technology (e.g., 2G or 3G). Unlike Jio, Rakuten Mobile adopted a virtualized architecture (vRAN), enabling a relatively less expensive network buildout compared to a traditional network operator. [179, 180]

Rakuten was awarded its spectrum, as is typical in Japan, rather than purchasing it at auction, as is typical in the United States.[181] Rakuten Mobile is not yet profitable as a network operator. While

175 Rakuten Announces Intent to Enter into Mobile Network Operator (MNO) Business, Rakuten investor relations, December 2017. https://global.rakuten.com/corp/news/press/2017/1214_02.html

176 Rakuten Mobile to Launch New Mobile Operator Service, Rakuten investor relations, September 2019. https://global.rakuten.com/corp/news/press/2019/0906_02.html

177 Rakuten Mobile Announces Full-Scale Commercial Launch; Unveils Enhanced "Rakuten UN-LIMIT 2.0" Service Plan, Rakuten investor relations, April 2020. https://global.rakuten.com/corp/news/press/2020/0408_01.html

178 Amin left Rakuten Mobile in 2023, and now is CEO at Aramco Digital.

179 Former Altiostar interview, November 2023.

180 As of November 2022, Rakuten Mobile had spent a cumulative $15 billion in capital expenditures (capex). Verizon and AT&T may spend $15 billion in capex in one year. US Cellular, the last remaining relatively sizable rural carrier in the United States with 4.6M subscribers, spends between $500M and $1B in capex per year. US Cellular announced sale of its wireless operations to T-Mobile USA in May 2024. https://investors.uscellular.com/news/news-details/2024/UScellular-and-TDS-Announce-Sale-of-Wireless-Operations-and-Select-Spectrum-Assets-to-T-Mobile-for-Approximately-4.4-Billion-in-Cash-and-Assumed-Debt/default.aspx

181 Rakuten was awarded AWS spectrum (1700/2100 MHz paired) initially, and then 700 MHz spectrum in 2023. https://www.lightreading.com/open-ran/rakuten-our-spectrum-s-the-problem-not-our-network

it initially projected getting to profitability in 2023, analysts project profitability in 2026.[182] As of March 2024, the operator has 2.7% market share in a competitive, well-served market. Mobile segment revenue, operating income, and mobile segment capital expenditures are shown in Figure 21.

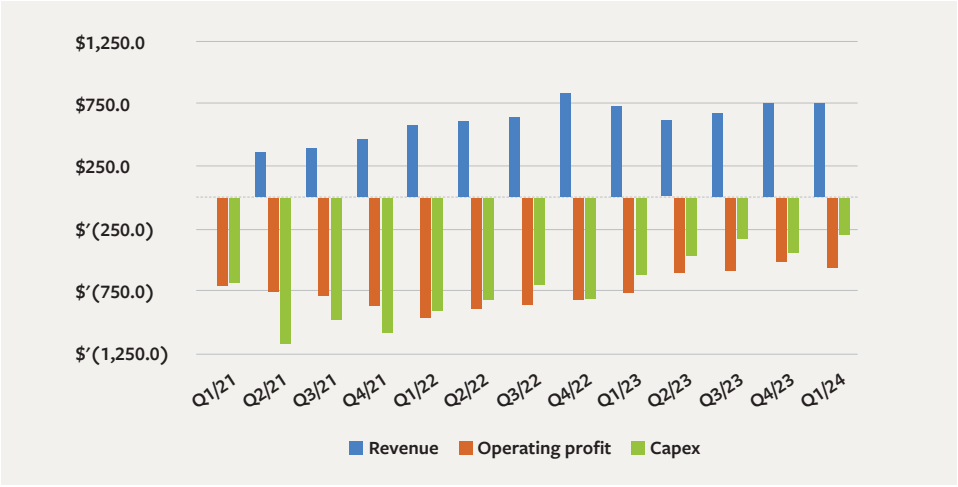


**Figure 21: Rakuten Mobile quarterly revenue, operating profit, and capex, Q1 2021–Q1 2024.**[183]

Subscribers and monthly average revenue per user (ARPU) are shown in Figure 22.

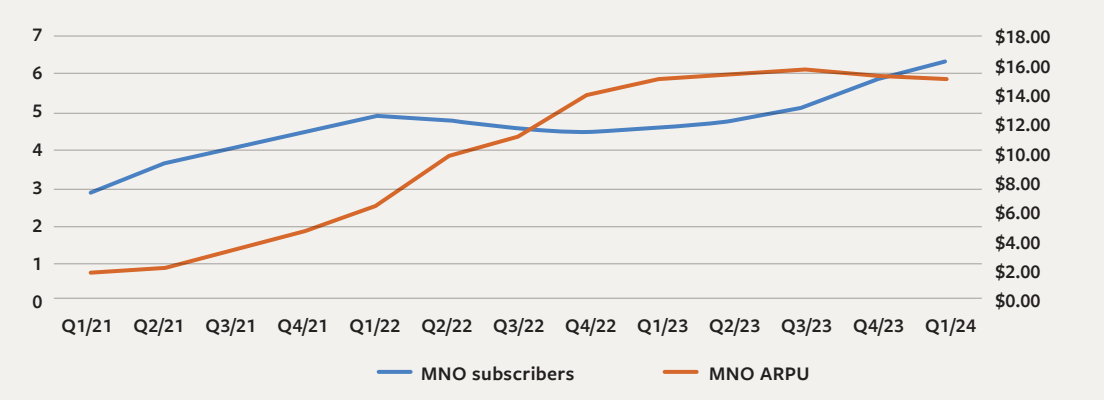


**Figure 22: Rakuten Mobile quarterly MNO subscribers (left y-axis, in millions) and ARPU (right y-axis, in dollars), Q1 2021–Q1 2024.**[184]

182 Spectrum-starved Rakuten will be loss-making until 2026 — analysts, Light Reading, January 2022. https://www.lightreading.com/open-ran/spectrum-starved-rakuten-will-be-loss-making-until-2026-analysts

183 Calculated based on Rakuten 24Q1 datasheet, using JPY130 = 1USD exchange to get the average exchange over the past five years. https://global.rakuten.com/corp/news/press/2024/0514_01.html

184 Ibid.

While Rakuten Mobile has yet to get to operating profitability, it provides a meaningful case study on several dimensions, including use of Open RAN techniques, integration of suppliers, and its capital-efficient rollout.

For example, the company unbundled the RAN from the outset. Rakuten Mobile, during its buildout, combined Nokia RUs with basebands from Altiostar.[185] Interviews indicate that Nokia agreed to this based on the force of Rakuten's commitment. Rakuten Mobile subsequently acquired Altiostar for $1 billion, creating the first case of a mobile network operator integrating a supplier in recent memory, and potentially the first of a network operator acquiring a network equipment supplier since AT&T acquired Western Electric in 1882.[186]

In 2020, Rakuten integrated Innoeye, a provider of process automation solutions. Rakuten also acquired cloud technology and application virtualization provider Robin.io in 2022.[187] Post-acquisition, Rakuten integrated Altiostar, Innoeye, Robin.io, and their respective tech stacks into its Rakuten Symphony organization. This is a service provider business that Rakuten stood up to provide Open RAN integration services to fellow network operators.[188] Customers include 1&1 in Germany, DISH in the United States, and AT&T. Rakuten itself touts a 40% capex advantage and 30% opex advantage relative to traditional network operators, as shown in Figure 23.

As of Q2 2022, New Street Research estimated that Rakuten Mobile had spent $15.8 billion cumulative in capital expenditures. New Street commented that, as a new network operator, Rakuten Mobile did not face a capex problem, but rather faces a revenue problem due to relatively low service fees. In 2023, Rakuten's total mobile network capex was roughly $2 billion, with lower outlays projected for 2024. These are less than a third of the capital expenditures of peer operator NTT DOCOMO, for example. Admittedly, DOCOMO's capital expenditures are in service of a significantly larger customer base. Further, Rakuten Mobile also pays roaming fees to roaming partner KDDI, so in a way, it is trading capex for opex.

185 Based on interviews with former Altiostar and Rakuten Mobile staff.

186 Rakuten Group to Acquire Mobile Industry Innovator Altiostar, Rakuten investor relations, August 2021. https://global.rakuten.com/corp/news/press/2021/0804_02.html

187 Rakuten Symphony agrees to acquire leading US-based cloud technology company Robin.io to deliver highly integrated telco-cloud for mobile, Rakuten investor relations, February 2022. https://global.rakuten.com/corp/news/press/2022/0228_03.html

188 Rakuten Launches Rakuten Symphony to accelerate adoption of cloud-native, Open RAN-based mobile networks worldwide, Rakuten investor relations, August 2021. https://global.rakuten.com/corp/news/press/2021/0804_04.html

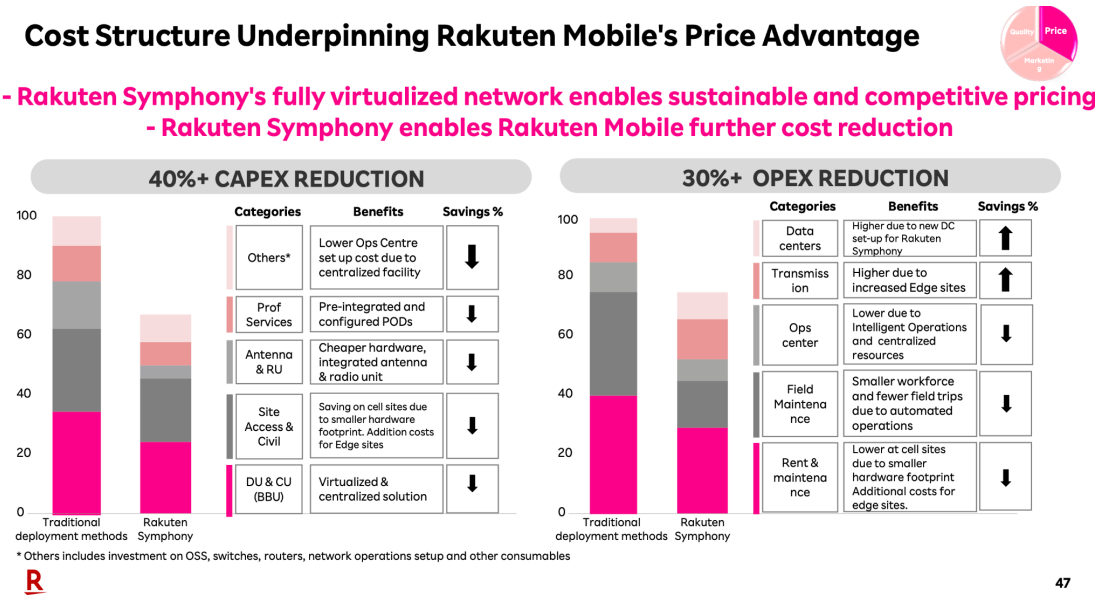


**Figure 23: Rakuten Mobile cost structure versus traditional network operators. Source: Rakuten Q2 2022 investor relations materials.**[189]

The Rakuten Mobile case study is still unfolding. As of this writing (November 2024), it provides several insights for network operators and policymakers worldwide.

- A relatively capital-efficient greenfield national network operator is possible. Through the combination of spectrum awards, a virtualized network harnessing Open RAN techniques, and roaming partnerships, Rakuten quickly built a network that covers 99% of Japan's 125 million people.
- Building such a network requires a determined architect with access to capital. Rakuten has funded network buildout to date through equity sales (e.g., floating shares in various subsidiaries, such as Rakuten Bank in April 2023) and debt issuances. Investment costs and operating losses from the Rakuten Mobile segment have offset profits from the company's other (profitable) business segments. As of November 2024, Rakuten Mobile had grown to 8.12 million subscribers. While still unprofitable as a segment, Rakuten Group stated that as a company, they had reached a phase of sustainable growth, and had exited the investment phase of network buildout.[190] The example shows patient

189 FY2022 Second Quarter Consolidated Financial Results . . . Rakuten Group, Inc. https://global.rakuten.com > doc > 22Q2PPT_E

190 Rakuten Group Q3 2024 earnings presentation, November 2024. Presentation Material 1 (Earnings Presentation). https://global.rakuten.com/corp/investors/assets/doc/documents/24Q3CEOPPT_E.pdf

capital is a necessity to build out a new greenfield operator, much as the example of Reliance Jio in India also shows.

- Building such a network requires an integrator capability. Based on its experience integrating Nokia, Altiostar, and other suppliers, Rakuten created a service arm, Rakuten Symphony, to provide similar integrator services for other network operators.
- Getting to profitability, particularly in already served, competitive markets, takes time and commercial scale; some analysts believe Rakuten Mobile will not be profitable on a standalone basis until 2026 at least. Rakuten Mobile itself believes it can get to cash-flow positivity at 10M subscribers.
- Rakuten Mobile's service largely depends on paired AWS (1700/2100 MHz) spectrum. Spectrum limitations have necessitated roaming agreements with carriers with lower band spectrum, such as competitor KDDI. This has necessitated payment of roaming fees to roaming partners. Rakuten was recently awarded 700 MHz spectrum, which should help with in-building coverage. Rakuten launched service using 700 MHz spectrum in June 2024.

# Has Open RAN catalyzed market entry by non-traditional suppliers?

Samsung, NEC, and Fujitsu are well-established network equipment suppliers with decades of experience serving network operator customers. Notwithstanding their long histories, analyst firm Omdia describes NEC and Fujitsu as "upcoming" in its network equipment provider landscape of 2023, and Samsung as a "major challenger" to the top three suppliers, Huawei, Ericsson, and Nokia. This is described in Figure 24.

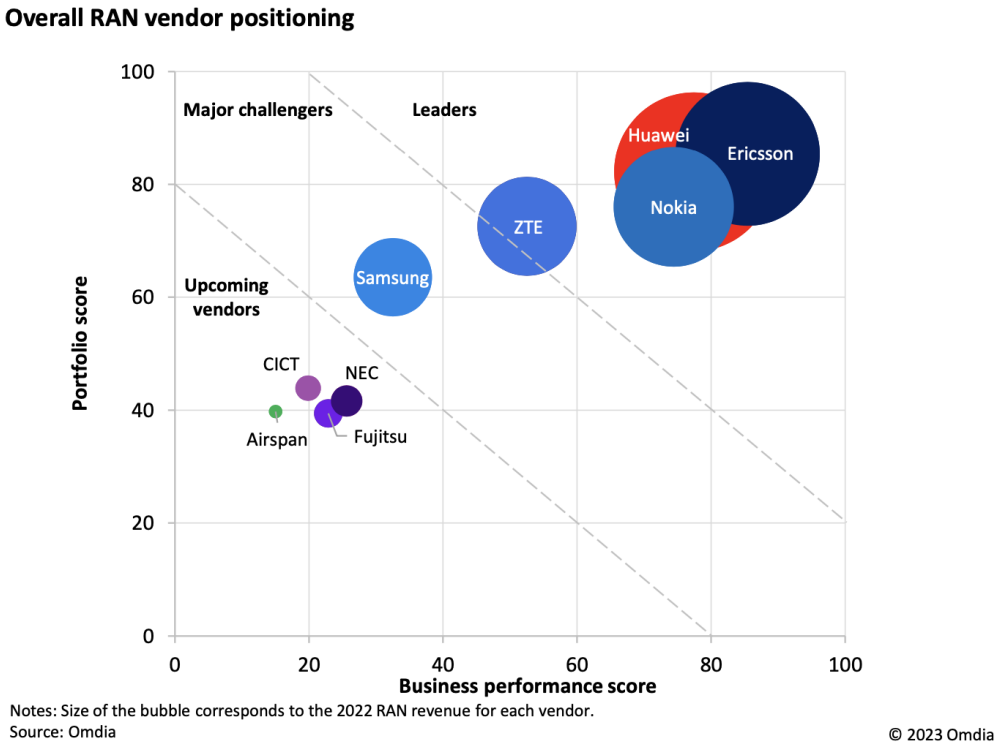


**Figure 24: Overall RAN vendor positioning, business performance versus portfolio. Omdia, Market Landscape, RAN Vendors 2023.**[191]

Samsung, NEC, and Fujitsu combined have close to 10% combined share in the RAN market, with the bulk of that going to Samsung. Samsung has gained share in the United States market

191 Report from Omdia available at: https://omdia.tech.informa.com/om030391/market-landscape-ran-vendors-2023

with the migration to 5G.[192] Other suppliers described as "upcoming" by Omdia include CICT from China, and Airspan from the United States.

While Samsung, NEC, and Fujitsu are hardly startups, their description as "upcoming" or as "major challengers" first highlights the concentrated nature of the RAN market. It also highlights that two factors — Open RAN, and also the blocking of Chinese network equipment suppliers in various countries — have in combination created an opportunity not just for new suppliers, but also for longstanding smaller suppliers to position themselves as alternatives to Chinese suppliers, or as substitutes for or complements to traditional suppliers like Nokia and Ericsson.

For NEC, whose network equipment business was largely limited to Japan, these two factors have meant an opportunity to work with new network operator customers outside of Japan. For Samsung, it has been an opportunity to expand its international RAN equipment business further. Thus, for both policymakers and network operators assessing the state of RAN supply, supplier diversity in the RAN market can mean not just facilitating market entry by newer entrants (such as Cohere or Mavenir or Eridan, all profiled later in this paper), but also new opportunities for existing suppliers. Indeed, more established suppliers, with more diversified business lines and experience selling to established network operators, may be more able to endure the long sales cycles required in selling into the RAN market. Network operator evaluation cycles for network equipment suppliers may last 18–24 months.

Suppliers domiciled in Japan (e.g., NEC and Fujitsu) benefit from experience working with NTT DOCOMO, which orchestrates multi-vendor RAN networks, and also with Rakuten Mobile's greenfield 4G/5G rollout. NTT DOCOMO has also created a service organization, OREX, to help fellow network operators (outside of Japan) with integration of Open RAN buildouts. OREX has created a joint venture with NEC, OREX SAI, and is targeting 5G Open RAN opportunities in the Philippines.[193]

In addition, newer suppliers, such as Altiostar (now part of Rakuten Symphony), Mavenir, Parallel Wireless, Cohere Technologies, MaxLinear, Eridan, and Movandi have also entered the RAN supplier market. Mavenir is a rollup of various telecom industry suppliers. Movandi and MaxLinear have targeted the 5G and 5G mmWave markets. Parallel Wireless positions itself as an Open RAN integrator for network operators. Eridan has roots in software-defined radio

192 Dell'Oro Mobile RAN report, 2023q2.

193 DOCOMO and NEC to Establish "OREX SAI" Joint Venture to Provide OREX Packages for Open RAN Global Deployments, NEC, February 2024. https://www.nec.com/en/press/202402/global_20240226_02.html

techniques for military applications and is entering the 5G RU market.[194] Profiles of these relatively newer suppliers are provided in Figure 25.

**Figure 25: New RAN supplier profiles**

| | Mavenir | Parallel Wireless | Altiostar Networks |
|---|---|---|---|
| **Year Founded** | 2005 | 2012 | 2011 |
| **HQ Location** | Richardson, TX | Nashua, New Hampshire | Tewksbury, Massachusetts |
| **Description** | Software provider and developer of cloud-native software applications for Wireless Service Providers. Also provides small cell equipment. Rollup of multiple companies (Comverse, Acision, Mitel, Ranzure, Argyle Data, and ip.access, among others). | Developer of an open and secure cloud native architecture to enable mobile operators to increase operational efficiency and reduce Open RAN operational complexity. Supports 2G to 5G. Provides hardware and software. | Software developer and provider that offers a virtualized baseband for 4G and 5G networks. |
| **Headcount** | 5000 | 670 | 550 (as of summer 2021) |
| **Capital Raised** | $1.7B | $39.41M | $347M (as of August 2021) |
| **Significant Customers** | Deutsche Telekom, DISH, Verizon Wireless, Telefónica | Vodafone, Optus, Telefonica, BT British Telecom, Zain Group, Vivacom | Rakuten, Airtel, DISH, Telefonica, STC, Etisalat |
| **Exit** | 2013 IPO as Mavenir Systems. Delisted in 2015. Filed S-1 in 2020 but canceled listing. | Privately held | Acquired by Rakuten (TKS: 4755) for $1B in August 2021. |

194 Eridan recently received a grant from NTIA for development of an Open RU. https://www.ntia.gov/page/what-they-re-saying-biden-harris-administration-awards-grant-wireless-innovation-fund-o

| | Cohere Technologies | Movandi | Eridan | MaxLinear |
|---|---|---|---|---|
| **Year Founded** | 2010 | 2016 | 2013 | 2003 |
| **HQ Location** | San Jose, CA | Irvine, CA | Sunnyvale, CA | Carlsbad, CA |
| **Description** | Developer of spectrum multiplier software to enhance the performance of mobile and wireless networks. Provides support across multiple generations. Positioning itself as a candidate wireless system for 6G. | Provider of RF chipsets and phase array antenna modules for 5G mmWave networks. | Developer of software-defined radios for spectrum-efficient and energy-efficient 5G networks and beyond. | Provider of RF and mixed-signal semiconductor products for cable, satellite, and other markets. Provide both RF chips and RF SoCs. |
| **Headcount** | 30 | 40 | 50 | 1750 |
| **Capital Raised** | $170.86M | $97.4M | $65.2M | Public: MXL (Nasdaq) |
| **Significant Customers** | Has investment from Intel Capital, Bell Ventures, and Telstra Ventures. Trials with Bell Canada, Vodafone. | Deployed by Rakuten, KT, SKTelecom, SingTel Optus, Telstra and other network operators. | Initially focused on software-defined radios for DARPA. Now developing RU products for Open RAN networks. | Provides a variety of products for WAN, cable, copper, fiber, data center, power management, microwave, mmWave markets. |
| **Exit** | Privately held | Privately held | Privately held | NAS: MXL (IPO in 2010) |

Commentary:

- Generally, these suppliers predate the appearance of "Open RAN" as a term. Many were founded by entrepreneurs with previous experience founding mobile infrastructure companies. The Altiostar team had prior experience at Starent (acquired by Cisco) and other successful startup entrants in the network infrastructure market. Similarly, Cohere Technologies was founded by alumni of Flarion Networks, which was acquired by Qualcomm. Movandi was founded by Broadcom alumni.
- Mavenir is a rollup of various telecom suppliers supported by private equity. It has gained traction mainly with greenfield network deployments. It was reported as a supplier to AT&T in December 2024.

- Altiostar's acquisition by Rakuten and subsequent rollup into Rakuten Symphony was historic, not just in terms of the outcome for venture shareholders, but also as it represented a rare integration into network supply by a network operator. Conversely, the fact that a US network supplier (Altiostar) was acquired by an international network operator (Rakuten, domiciled in Japan, a US ally), at a time when the US government publicly lamented the absence of "domestic" network suppliers, has been observed by some as lacking coherence. Cisco and Qualcomm, both US suppliers to mobile operators, were both shareholders at the time of the exit to Rakuten, which was also an existing shareholder. (Thus, Cisco and Qualcomm, as investors in Altiostar, both had the opportunity to submit a counter-offer to acquire Altiostar.) In any case, the example of Altiostar, in addition to the other suppliers (e.g., Cohere, Eridan, MaxLinear, Movandi, etc.) listed above, provides evidence that the US market does indeed continue to produce new network equipment suppliers.
- The combination of 5G mmWave and the resultant network densification (e.g., more small cells), and the initial attention around Open RAN and greenfield deployments, has helped catalyze attention by new suppliers. With that said, the recent pullback in 5G infrastructure spending has posed challenges for suppliers targeting the 5G and 5G mmWave market.

# Commentary and Recommendations

Open RAN is at a crossroads. Open RAN spending reached 5–10% of the total RAN market, thanks in part to the rollout of greenfield networks. But those rollouts have slowed. Further, the growth in "single-vendor Open RAN" networks have perhaps diluted the original meaning of Open RAN as a means of unbundling the RAN to increase hardware and software supplier diversity and interoperability.

While Open RAN adoption has slowed in the context of 4G and 5G networks, the insights from Open RAN deployments are timely in the context of planning for 6G networks. For example, unbundling the RAN requires an integrator to stitch the constituent elements together. That party can be the network operator, a trusted supplier, or a third party, such as an IT services firm or a specialist like Rakuten Symphony or DOCOMO OREX. Operators looking to harness Open RAN without depending on traditional suppliers will need to cultivate (or re-cultivate) these skills, or partner with integrator specialists.[195]

A second insight is that thoughtful definition of what features are essential and what truly are legacy will be important when planning for 6G. Various network operators interviewed for this report commented that they want to see Open RAN suppliers reach "feature parity" with traditional suppliers. How important will support of 2G or 3G be in a 6G era? 2G networks have had surprisingly long life due to various embedded devices using 2G modules. Still, should new 5G/6G suppliers have to support 2G or 3G, and for how long? In our 2020 paper, *Security Implications for 5G Networks*, we recommended that network operators migrate to standalone 5G as quickly as possible, for service flexibility reasons and for security reasons.[196] We reiterate that recommendation here.

195 Interviews over the course of this report indicated that the long history of co-specialization or co-dependency with network equipment suppliers has led to a withering of network operators' integration skills. One interviewee cited that NTIA RU funds were useful in that they helped smaller operators hire staff with relevant integration skills.

196 Metzler, Security Implications of 5G, 2020, published via the UC Berkeley Center for Long-Term Cybersecurity. https://cltc.berkeley.edu/wp-content/uploads/2020/09/Security_Implications_5G.pdf

## RECOMMENDATIONS FOR POLICYMAKERS

The steady cadence of legislative and executive activity across multiple presidential administrations in the United States shows that network infrastructure remains a topic of relative consensus. Below, we provide recommendations for ways to further nurture supplier diversity in the network equipment segment, in the United States and beyond.

### Fragmented grants may lead to fragmented "point solutions"

At a high level, the relatively fragmented nature of support from NTIA bears risk of supporting point solutions to point problems. As the FCC Rural 5G Fund is still unspent, we recommend investigating targeted, consolidated opportunities that would meaningfully impact both the state of 5G deployment in underserved areas and also the state of supply. While the $9 billion in the FCC Rural 5G Fund may be insufficient to fully fund 5G rollout across rural swaths of the US, Puerto Rico, and the Virgin Islands, $9 billion represents a meaningful amount in the context of the RAN market, which globally represents a $40 billion market within the $100 billion telecom equipment market. Thus, while smaller grant opportunities are helpful for small businesses and startups, concentrated, directed, and larger application of funds could be more impactful in shaping established RAN supplier or network operator behavior.

- Recommendations for NTIA:
    - NTIA's Public Supply Chain Wireless Innovation Fund, funded through the CHIPS and Science Act of 2022, is a positive first step towards facilitating RAN supplier diversity in the US market. We have commented already that allocating NTIA funds towards operator R&D facilities, as NTIA did in providing funds to AT&T and DISH for development of Open RAN test facilities, will not meaningfully impact the state of RAN supply, nor will it materially impact DISH's chances of success as a national network operator. Conversely, grants of a similar amount (e.g., the $50 million provided to DISH) could materially impact the trajectory of a new technology supplier, such as a startup RU supplier.
    - We commend NTIA's efforts to seek a multiplier in having bidders responding to RU grant opportunities sign an LOI with a network operator. Bidders noted that, for smaller network operators, NTIA funds helped offset the cost of network operators hiring new staff for the purpose of RAN technology evaluation.
    - Startup entrants into the mobile infrastructure market have a long incubation cycle (5–10 years), and operators themselves have long evaluation cycles (18–24 months) and upgrade network generations every 10 years, with mid-cycle upgrades.

Thus, inducing new suppliers and meaningfully changing the state of RAN supply will take time and consistency. NTIA should continue to provide consistent funding opportunities. We recommend that the Public Wireless Supply Chain Innovation Fund, once depleted, be renewed as it will likely take multiple iterations to meaningfully impact the state of RAN supply. Here we point to the example of NEDO in Japan as an example of providing consistent funding opportunities to nurture wireless technologies. Consistent funding opportunities will help startup suppliers traverse the "valley of death." NIH grants for life sciences have had this effect in nurturing biotech startups.

- NTIA has helped fund development of Open RAN test and engineering centers operated by DISH and by AT&T, and also provided funding to various universities. NTIA should continue university funding opportunities, with the goal of developing a talent base to both develop and manage RAN networks.
- It took three years for states to complete their BEAD plans after the allocation of $42.5 billion for the BEAD program in the Infrastructure Investment and Jobs Act of 2021. More rapid development and approval of plans could have helped improve the state of broadband access more quickly.

- Recommendations for the FCC:
  - The FCC should measure the state of RAN and telecom equipment supply as part of its broadband measurement process.
  - We recommend fully funding the FCC rip-and-replace fund, which is underfunded by at least $3 billion.[197] The above recommendation — clarity on the state of supply — would help in understanding dependencies and potential vulnerabilities. We further recommend prioritizing allocation toward development of open and resistant networks.
  - The Rural 5G Fund remains unspent years after its creation. The FCC waited to complete the process of broadband measurement, but in doing so, five years have elapsed. The FCC should act with greater urgency to allocate the Rural 5G Fund.
  - In its August 2024 Report and Order (in the Matter of Establishing a 5G Fund for Rural America), the FCC indicated its intent to provide an additional $900 million in potential support for Open RAN deployments in conjunction with the $9 billion Rural 5G Fund, and to grant the ability for network operators to seek limited extensions in their 5G deployment milestones, if deploying Open RAN necessitates additional time. We commend the FCC's efforts to provide a multiplier for adop-

197 As of December 2024, the US Senate had allocated funding for rip-and-replace operations as part of the National Defense Authorization Act.

tion of Open RAN equipment, and recommend more wholesale support of Open RAN solutions with the Rural 5G fund.
    - The FCC should also seek synergy with NTIA funding opportunities, as the Competitive Carriers Association and others have commented in various dockets.
    - Congress should renew the FCC's auction authority with all haste. The FCC needs the ability to engage in long-term planning; the work of identifying potential spectrum bands, developing band plans, and ultimately conducting auctions typically lasts longer than the term of one presidential administration, and often spans multiple administrations. Hampering the FCC ultimately hurts national competitiveness.

- Additional funding recommendations:
    - The Department of Commerce, via NTIA, should provide consistent SBIRs for the goal of nurturing Open RAN suppliers and chip suppliers for RAN networks. Other potential department sponsors of Open RAN SBIRs include the Department of Defense, and potentially the Department of Energy, if emphasizing energy-efficient wireless networks.
    - Strategic venturing
        - The intelligence and defense communities have sought to achieve a capital multiplier via strategic venturing. Examples include In-Q-Tel and DIU (Defense Innovation Unit). Startups raising capital from In-Q-Tel and accelerating defense procurement via DIU solicitations have used proof of government demand as a way to de-risk themselves in the eyes of commercial venture investors; in return, government customers can take advantage of a private capital multiplier.
        - We recommend exploring similar strategic venturing opportunities for Open RAN. The Defense Department and NTIA have already partnered on a 5G Challenge in 2023.[198] This could be through DIU if for the purpose of serving defense customers. It also could be constructed as NTIA-ARPA, much as DARPA inspired ARPA-E or HSARPA. This also could be facilitated through guidance to the private sector investment community on what capabilities the government is looking to nurture.

- Facilitating liquidity in the network operator market: "Telly Mac"

198 https://5gchallenge.ntia.gov/2023-5g-challenge

- Network operators will often issue debt for the purpose of network investments or spectrum purchases. Recent examples include debt issuances from US Cellular. Smaller and/or privately held network operators may not have the same direct access to fixed-income markets. With the goal of fostering greater liquidity in the smaller network operator market, we recommend potentially forming a "Telly Mac" that would facilitate bundling of compliant network operator debt issuances, much as Fannie Mae (Federal National Mortgage Association, originally created in 1938) and Freddie Mac (the Federal Home Loan Mortgage Corporation, created in 1970) help provide liquidity to the mortgage market. Fannie Mae and Freddie Mac both create secondary markets for mortgages by bundling and securitizing them, and selling them to investors as mortgage-backed securities. A similar capability could help create liquidity for network operators when issuing debt for the sake of network investments.
- The US does not currently have a domestic development bank. It is noteworthy that the Department of State can partner with USAID to provide Open RAN funding to international allies, yet a similar domestic capability does not exist. Telly Mac would be a way to fill such a gap.

- 6G Challenge
  - DARPA has used various challenges to draw forth talent and innovation and direct it toward some technical hurdle, whether autonomous vehicles, robotics, or software-defined radios. We recommend that the NTIA continue on the path set with its 2023 5G Challenge, and begin planning for a series of 6G challenges, with a focus on open, resilient networks provided by non-traditional suppliers.

- Warp Speed for Wireless:
  - During the Covid-19 pandemic, the US government — specifically the Department of Health and Human Services and the Department of Defense — carried out Operation Warp Speed, which pre-funded vaccine development and manufacture.[199] This de-risked development and distribution of multiple different vaccines effective against coronavirus. The US government was able to develop and distribute vaccines relatively quickly, and also was able to provide vaccine supply to allied nations. This was a powerful case study of the federal government directing the innovative capabilities of multiple companies at a specific problem, and then supporting the distribution of that innovation out to the public.

199 https://www.gao.gov/products/gao-21-319

- As described in this paper, in recent years the US government has created various funding pools, broadly for the purpose of furthering broadband access, such as providing $42.5 billion to NTIA for BEAD; $9 billion to the FCC for a Rural 5G Fund; and $1.5 billion to NTIA for its Public Wireless Supply Chain Innovation Fund. This has been admirable and has created significant funding opportunities. With that said, fragmented funding bears the risk of fragmented outcomes.
- During the 2G rollout era, an industry rule of thumb for the full cost (including equipment, mast, and civil costs) of a base transceiver station in the US was $100,000. At 100,000 base stations, this comes to $10 billion. (This does not include any spectrum acquisition costs, or handset procurement costs.) Today, a national carrier like T-Mobile USA or AT&T might spend $15 billion in capex, of which a third typically goes to capital expenditures on network equipment. Thus, the sums being put forward by the federal government — if concentrated — are meaningful enough to shape the plans of even established network operators, or to shape national rollouts.
- Thus, with an eye to more transformative impact, we recommend that the US government, and allied governments, contemplate an Operation Warp Speed for wireless. If governments truly want open, resilient wireless networks for 5G or 6G, more concentrated directing of support could help deliver it. Further, allied nations, such as members of the Quad, could pool their resources to provide further scale for such an initiative. With 5G rollouts slowing in advanced wireless nations, this is an apt time to assess how to consolidate and target resources towards 6G, and ensure that 6G leverages open network techniques.

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Prior to returning to campus to teach, Jon founded Blue Field Strategies, a consulting firm helping infrastructure clients such as network operators and IT services firms accelerate service innovation, via market research and entry support; market and policy advocacy; and direct and indirect investment sourcing, due diligence, and post-investment operationalization. Jon has supported new business launches in media; edtech; wireless infrastructure; geolocation; events; services and more. Prior to that, Jon was Business Development Director at Rosum Corporation (acquired by TruePosition), a pioneering location technology company augmenting the reach of GPS indoors. At Rosum he drove business development in telecom, defense and IoT markets, and also was responsible for government affairs, public relations and standards.

Jon completed his MBA/MA-Asian Studies at the Haas School of Business. There he co-founded the Berkeley Asia Business Conference, and also authored a thesis comparing the innovation ecosystems and new venture formation in Silicon Valley and Japan. His interest in clustering and regional advantage stems from this experience. Jon also has a B.A. from the University of Michigan.

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