Considerations on the equipment ecosystem for 5G private networks in 3.4-3.8 GHz - Final Report Public

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About Plum

Plum offers strategy, policy and regulatory advice on telecoms, spectrum, online and audio-visual media issues. We draw on economics and engineering, our knowledge of the sector and our clients' understanding and perspective to shape and respond to convergence.

About this study

This study for EZK / Agentschap Telecom considers how the 4G/5G ecosystem for private mobile networks is developing in Europe with a view to spectrum reservation for local private networks in the 3.4-3.8 GHz band.

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Summary

The Ministry of Economic Affairs and Climate (MinEZK) needs to better understand how the equipment ecosystem for 4G/5G private networks is developing in Europe with a view to assessing the use of 3.4-3.8 GHz to support these networks in The Netherlands. The Ministry is also interested in influencing factors from regions/markets outside Europe and how relevant the exact allocation of spectrum for private network use in the C-band (mainly in the 3400-3800 MHz) is to enterprises wanting to make the best use of the products and solutions possible with the ecosystem available at these frequencies.

In this report we set out key issues around mobile private networks operating in these frequencies and the supporting ecosystems, together with our understanding of the spectrum situation and constraints it might impose on allocations.

The report is based on the prior experience of the project team and a review of relevant literature and a small number of interviews carried out with key players. Interviews with base station vendors, a vertical also providing base stations and devices, a module manufacturer and an antenna manufacturer enabled us to answer questions not covered with our desk research.

This is our final report and it contains the output of the research and interviews carried out together with the synthesis of the material obtained and our conclusions.

4G/5G private networks are developing quickly around the world and the most advanced countries are China, the United States and Germany. The overall global market for private networks within enterprise verticals is expected to reach US$109 billion by 2030 according to ABI Research in March 2022.

In the 3.4-3.8 GHz band Germany was the first EU country to make a frequency reservation for local networks at 3.7-3.8 GHz. Sweden has also made spectrum available for private networks in 3.76-3.80 GHz. We could not find any relevant examples of spectrum being made available for assignment to private networks at the lower end of the band (3.4-3.5 GHz). Some countries are making spectrum available for private networks above 3.8 GHz including the UK (3.8-4.2 GHz) and France (3.8-4.0 GHz for test licences). Norway has made spectrum available for test licences (3.8-4.2 GHz). There is evidence of demand for mobile private networks in such spectrum from the assignments being made in Germany and the UK.

There are leasing / sub-licensing arrangements specified for industry verticals in some countries (e.g. in Denmark, Finland, France) for the 3.4-3.8 GHz band, which work as an alternative to a reservation / set-aside but it is not clear so far what demand has emerged via this spectrum access method.

The radiolocation service in 3.1-3.4 GHz creates a problem for operation at frequencies immediately above 3.4 GHz and several European administrations have avoided assigning the bottom 10 MHz of the 3.4-3.8 GHz band to protect services in the lower adjacent band. In the Netherlands the requirements for protection of the radiolocation service applies nationwide. The EU Implementing Decision 2019/235 specifies clear and stringent out-of-band emission limits to protect radiolocation and allows for a 10 MHz guard band below the 3.4 GHz band edge. The most likely workable mitigation for mobile private networks is the use of a guard band above 3.4 GHz, which will reduce the amount of spectrum available for these networks but may still provide sufficient spectrum (e.g. 80 MHz). Imposition of a power limit for mobile private networks in addition to a guard band will also reduce the risk of interference (these networks are not likely to need to transmit at the powers used by macro cells in public networks). However, whether such measures will completely avoid the need to fit additional filters to mobile private network equipment to ensure no disruption of the radiolocation service requires further investigation.

There was a reluctance on the part of some of the new equipment vendors approached to contribute to the study to adapt their network equipment to specific RF environments that would require modifications like additional filtering (either because these networks will be operating at the band edge or of a guard band not fully protecting adjacent services). These players want to design and deploy standard equipment that enables them to secure manufacturing and operational economies of scale. It is difficult to modify / add additional filtering to modular small cell implementations, for example. Adaptations might also be costly (e.g. costs and mechanical issues for filters, diplexers, and other RF components for small cells). There is less pressure on device vendors from these restrictions.

It is still relatively early in the lifecycle of the 5G network equipment ecosystem for verticals and local network deployments, although activity by smaller / alternative vendors is building to compete with the larger vendors in these sectors. Today, more than 90% of the equipment for commercial and mobile private networks is provided by five major manufacturers: Huawei, Ericsson, Nokia, Samsung and ZTE. The device ecosystem is also developing and while there are a growing number of mainstream 5G devices operating in the band, the ecosystem for other CPE and modules is still at an early stage and will take another year or more to fully develop as demand for private network equipment increases. The advent of Open RAN and its opening of more options for building networks with defined interfaces and simplified radio units may lower barriers to entry for private 5G network equipment development and production.

Looking forward we note that the European Commission has mandated CEPT to consider the use of 3800-4200 MHz for terrestrial wireless broadband systems providing local area network connectivity. Equipment and device vendors are looking at the development this would entail. While solutions across the 3400-4200 MHz band can be supported by 3GPP band n77 vendors might focus on the upper part of the band (e.g. 3700 MHz upwards) for private network use and adapt their product roadmaps accordingly. CEPT will provide its final view on the Mandate by March 2024 and it is anticipated that an Implementing Decision will be published in the following year.

Our key finding from the research undertaken for this project is that there is significant reluctance among equipment vendors and especially the newer entrants to this market (including Open RAN providers) to develop solutions that meet the block edge mask requirements for protection of the radiolocation service operating in 3.1-3.4 GHz. Application of a suitable guard band and limitation of power might provide a means of achieving suitable mitigation but the detail of this requires further study.

The established vendors serving the MNO market are able to provide suitable equipment to meet these requirements, but their price points are unlikely to be attractive for private network builders. If spectrum is allocated in 3.4-3.5 GHz for private networks, there is a risk that the cost of providing solutions will deter private network investment.

1 Introduction

The Ministry of Economic Affairs and Climate (MinEZK) responsible for spectrum policy in the Netherlands needs to better understand how the equipment ecosystem for 4G/5G private networks is developing in Europe with a view to progressing a frequency allocation to support these networks in The Netherlands. The Ministry is also interested in influencing factors from regions/markets outside Europe and how relevant the exact allocation of spectrum for private network use in the C-band (mainly in the 3400-3800 MHz) is to enterprises wanting to make the best use of the products and solutions possible with the ecosystem available at these frequencies. Summer 2022, MinEZK set out the intended 3.5 GHz band plan for public consultation, containing the proposal to reserve the 3.4-3.5 GHz for local private networks and to allocate the remaining part of 300 MHz to public mobile networks. The consultation responses proved it necessary to review the band plan proposal. A specific need that emerged was to improve the understanding about how the international equipment ecosystem for local private networks will develop in the coming years and how that could affect the choices to be made for the band plan, specifically regarding the reservation of spectrum for local private networks.

In this report we set out key issues around private networks operating in these frequencies and the supporting ecosystems, together with our understanding of the spectrum situation and constraints it might impose on allocations.

The report is based on the prior experience of the project team and a review of relevant literature and a small number of interviews carried out with key players. Interviews with base station vendors, a vertical also providing base stations and devices, a module manufacturer and an antenna manufacturer enabled us to answer questions not covered with our desk research.

This is our final report and it contains the output of the research and interviews carried out together with the synthesis of the material obtained and our conclusions.

This remainder of this report contains the following sections:

- Section 2: 5G private networks with an analysis of the use and characteristics of 5G private networks, 5G private networks market trends, ecosystem and supply side and an analysis of base station and device options and limitations.

- Section 3: Spectrum options setting out the availability and constraints on use of spectrum, analysis from other administrations of provision of private networks and potential future allocations and their implications for spectrum used for private networks in the 3.4-3.8 GHz band.

- Section 4: Provides further analysis of the information set out in previous sections and in particular factors driven by choice of spectrum.

- Section 5 sets out our conclusions.

Use of the ✂ symbol indicates where commercially sensitive information has been redacted.

2 5G private networks

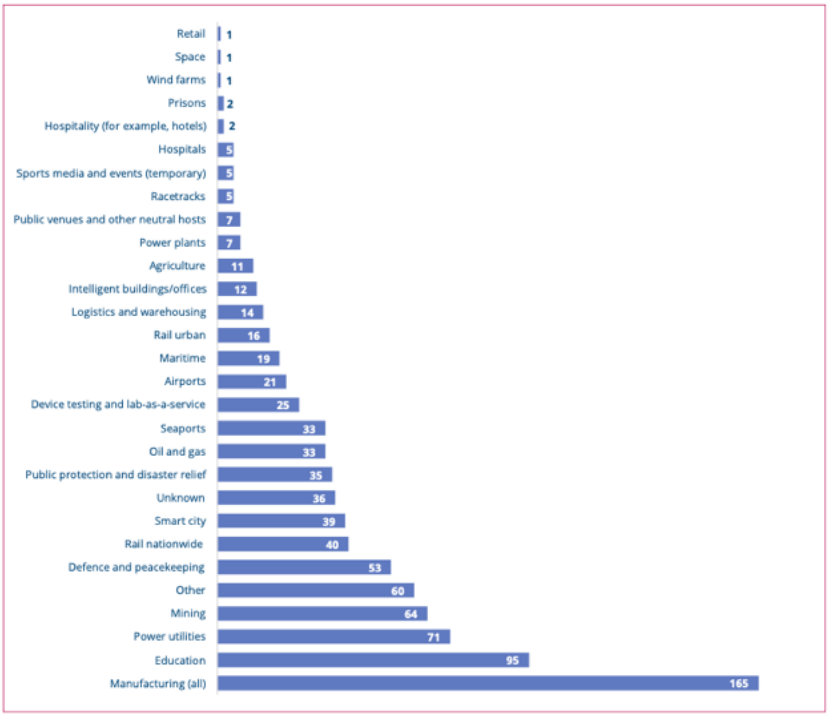
2.1 Use and characteristics of 5G private networks

A wireless private network is a network that provides broadband connectivity to a closed user group. Wireless private networks[1] currently use various wireless access technologies such as DECT, WiFi, cellular technologies (2G, 3G, 4G, 5G), or dedicated industrial technologies such as IEEE 802.15.4. Spectrum used can be the MNO's spectrum, dedicated spectrum for private networks or unlicensed spectrum. Wireless private networks can be built and operated by a vertical or enterprise or operated by a mobile operator or via a mix of responsibilities between the players. In this analysis, we focus on the use of 5G for wireless private networks and we also consider 4G when the private networks are easily upgradable to 5G.

2.1.1 4G/5G private networks deployed by vertical stakeholders

According to a survey carried out by the GSA and the European 5G Observatory, the main sectors of the economy that deploy 5G private networks are manufacturing which comes as the first vertical sector deploying private mobile networks today, education, power utilities and mining. Defence, national railways and smart cities also represent a significant number of private mobile networks. It should be noted that GSA figures cover 4G and 5G contracts worth more than €100,000.

Figure 2.1: Number of identified customers deploying private mobile networks (World)

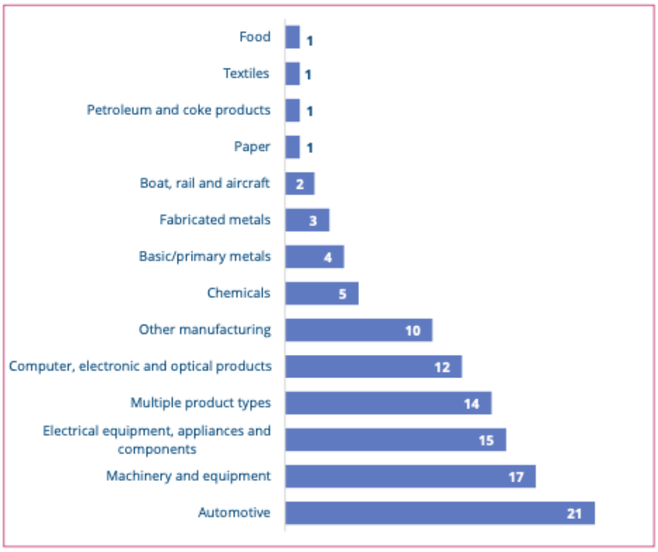


Source: GSA (in trials and commercially, by sector - base: 889 organisations)

The manufacturing vertical covers various industries and among them, automotive comes first, followed by machinery & equipment and electrical equipment.

[1] In this report, we also use "private mobile networks" for networks using cellular technologies such as 4G or 5G.

Figure 2.2: Number of manufacturing customers deploying private mobile networks (World)



Source: GSA (in trials and commercially by subcategory where identified - base: 103 organisations)

2.1.2 Possible configurations and main characteristics of 4G/5G private networks

When considering these networks it is important to understand technology choice and the size of mobile private networks. Also the type of services supported by mobile private networks.

2.1.2.1 Mobile private networks size and technology

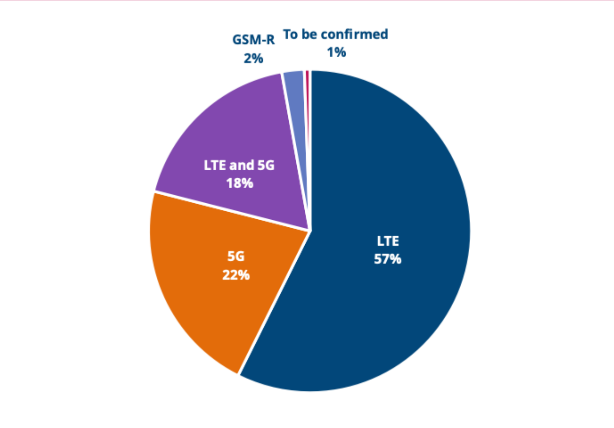
Large-scale private networks such as GSM-R deployed by national railway companies represent the largest mobile private networks in size and operate on dedicated spectrum in Europe.

As far as private 5G networks' coverage is concerned, the demand for indoor solutions is much greater than outdoors. Private 5G networks generally need to be compact both in capacity and size and their required capacity may be less than that of a macro network (although the use characteristics may be different). Local private networks generally cover reduced geographical areas and can also be interconnected to connect different production sites for industries.

2.1.2.2 4G/5G private networks distribution

In 2022, 5G is supported by 40% of the mobile private networks identified by GSA on a worldwide basis. LTE still represented between 57% and 75% of the total in early 2022 (the GSA report was published in August 2022).

Figure 2.3: Private mobile network customers by technology used (World)



Source: GSA (base: 889 catalogued customers deploying private wireless networks)

2.1.2.3 Type of services supported by 5G private networks

5G is bringing many enhancements compared to 4G with Ultra-Reliable Low Latency Communication (URLLC), enhanced Mobile Broadband (eMBB), and massive Machine-Type Communication (mMTC).

Today, almost all 5G private networks provide eMBB services, with higher speeds and more capacity than 4G networks. IoT services are currently provided on 4G technologies such as NB-IoT and LTE-MTC. LPWA (Low-power wide-area network) technologies such as LoRaWAN or Sigfox use unlicensed spectrum and are out of the scope of this study.

As an example, Samsung's private 5G solution delivers applications to provide various services. Currently, the supported applications are as follows:

- IP Multimedia Subsystem (IMS) solution for voice communication.
- Mission Critical Push-To-All (MCPTX) solutions for mission-critical voice or video group communication.
- Video surveillance platforms for monitoring and analysis of video information.
- IoT solutions for device controlling such as sensors, machines, and facilities.
- Drone solutions for controlling drones.

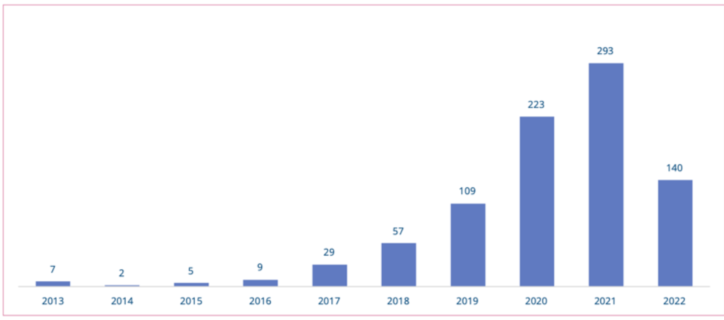
2.2 5G private networks market trends

In this section, we analyze how the 5G private market is developing today in Europe and around the world. We also present market forecasts for the coming years and identify main market trends for the 5G private market.

2.2.1 The 5G private network market today

The 4G/5G private network market tracking from GSA shows that activity started in 2013 and reached 293 new private networks (over €100,000) in 2021. Figures for 2022 should be quite similar as mid-year figure was 140 new networks.

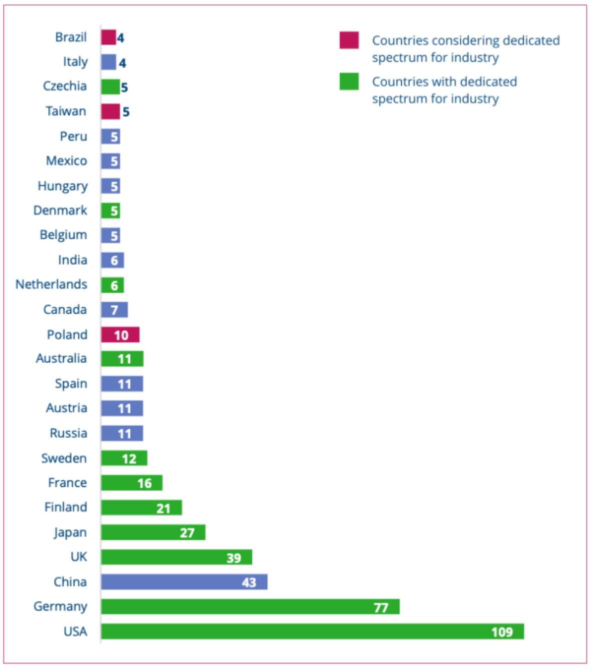
Figure 2.4: Private mobile network customers, by year announced (World)



Source: GSA

USA leads the ranking with a lot of activity in the CBRS band, followed by Germany, China and the United Kingdom.

Figure 2.5: Number of private network customers by country

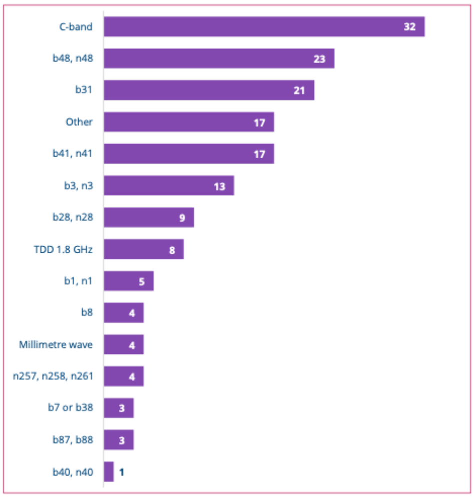


Source: GSA (base: 498 organisations, where country has been identified)

Note: blue bars correspond to countries with no dedicated spectrum for private networks

In terms of spectrum used for 4G/5G private networks, the C-band comes first (both "C-band and b48/n48 which corresponds to CBRS), followed by b31 (450 MHz), b41/n41 (2.5 GHz in the USA). Then come frequency bands largely used by MNOs such as b3/n3 (1800 MHz) or b28/n28 (700 MHz).

Figure 2.6: Spectrum bands used for private mobile networks (World)



Source: GSA (number of customer deployments identified using each band - base: 203 organisations)

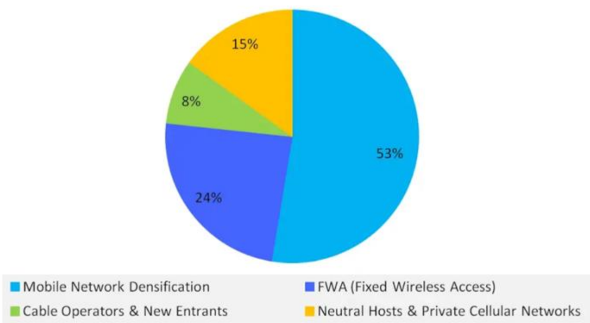
2.2.2 Outside Europe

2.2.2.1 USA

In the USA, mobile private networks are mainly developing in the CBRS (Citizens Broadband Radio Service) band. CBRS covers 150 MHz (3.55 to 3.7 GHz) of spectrum only assigned in the USA and it can be used for mobile private networks.

In 2020, neutral hosts and private cellular networks represented only 15% of small cells shipments in the USA.

Figure 2.7: Distribution of LTE-based CBRS small cell shipments by use case: 2020 (%)



Source: SNS Telecom

As of March 2022, the OnGo Alliance reported that there were 208,000 CBRS base station devices (CBSDs) deployed in the CBRS band, a 100% increase over the previous year.

Today, most CBRS devices are 4G devices and there was very limited availability of 5G devices in October 2022[2]. This is primarily because 5G chipsets do not yet support the CBRS band.

It should also be noted that hyperscalers such as AWS are now offering private network support for the CBRS band in the USA. AWS offers base stations rental and core network support with its AWS Private 5G service.

2.2.2.2 China

In China, 5G private networks are built by the Chinese MNOs. In July 2022, there were 6,518 private 5G networks, up from 1,655 a year ago, according to Communications World and 5,325 in May 2022 according to the Ministry of Industry and Information Technology[3]. Main verticals using these private networks are smart factories (1,000 5G private networks), hospitals (600), smart mines (200), smart grids (180), and ports (89).

According to the Chinese Ministry of Industry and Information Technology, China had over 2.1 million 5G base stations at the end of August 2022. The 700 MHz, 3300 to 3600 MHz and 4800 to 5000 MHz bands are currently used for 5G networks in China. The 26 GHz band might also be used for 5G.

Figure 2.8: frequency bands used by MNOs in China

Band	Frequency	MNO
	703-798 MHz	China Broadnet
n41	2.515 - 2.675 GHz	China Mobile
n78	3.4 - 3.5 GHz	China Telecom
n78	3.5 - 3.6 GHz	China Unicom
n79	4.8 - 4.9 GHz	China Mobile

Source: Plum Consulting

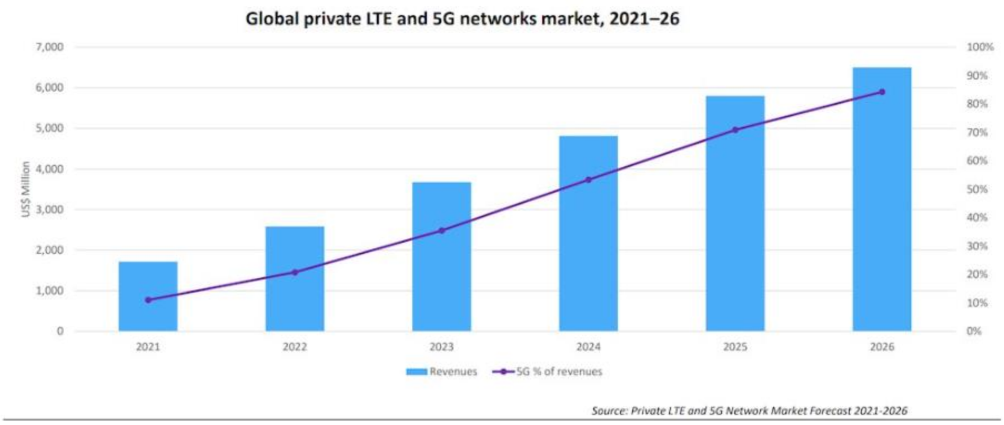
2.2.3 4G/5G private networks market forecasts

It is expected that 5G private networks should continue to develop quickly around the world. Market forecasts for the coming years show a continuous growth of this market:

[2] As an example, the RFWEL site references only two n48 5G devices but 83 4G devices for the LTE band 48 (https://wdi.rfwel.com/wireless-devices-info/cellular-bands/nr-n48/ retrieved November 7, 2022)

[3] https://finance.sina.com.cn/tech/2022-05-22/doc-imizirau4200986.shtml?finpagefr=p_114

Figure 2.9: Private LTE and 5G network market forecasts

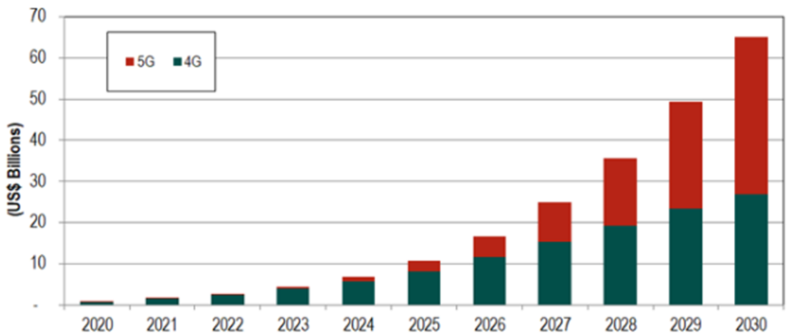


Source: Nokia/ABI Research

In March 2022 ABI Research announced that the overall market for private networks within enterprise verticals will reach US$109 billion by 2030. This includes radio access network, edge & core deployments, as well as professional services revenues. However, at the same date, research and consulting firm Dell'Oro Group presented a more pessimistic view on the US market and reduced its expectations for sales of equipment running in the CBRS band.

5G will represent more than 50% of the mobile private market in 2029 according to ABI Research:

Figure 2.10: Private networks revenue by technology – World market, 2020-2030



Source ABI Research

2.2.4 3GPP standardisation and 5G private networks

3GPP release 16 brings many functionalities necessary for private network in the industry such as very high connection density, reduced latency, five "9" reliability, non-public networks support, Industrial IoT support for Time Sensitive Networks (TSN) and direct communication between end-devices (SideLink). These functionalities are only available with equipment and devices compatible with 3GPP Release 16 published in July 2020.

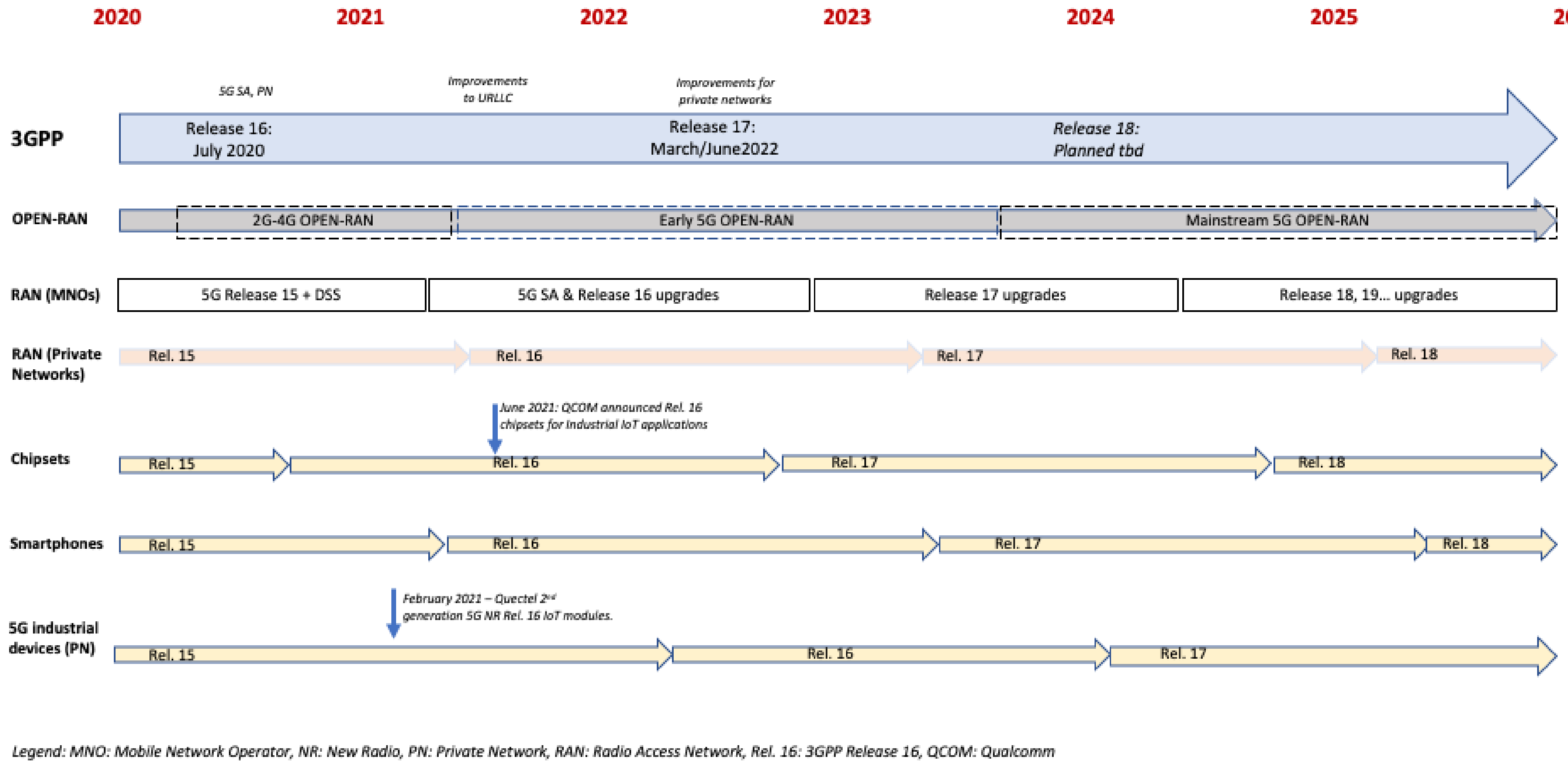
Figure 2.11: Functionalities necessary for 5G private network in the industry and 3GPP Releases

RAN part	Release 15	Release 16	Release 17	Release 18
Connection density (1 million/km^2)	Partially	Partially	Yes	Yes
Latency (< 10 ms)	No	Partially	Yes	Yes
Reliability (99.999% under 10 ms)	No	Partially	Yes	Yes
Localization (1 meter accuracy)	No	Partially	Partially	Yes
NPN: Non-Public Networks (Private)	No	Partially	Yes	Yes
Industrial IoT (TSN support)	No	Partially	Partially	Yes
SideLink (Direct Communication between end-devices)	No	Partially	Partially	Yes

Source: Adapted from Siemens

The figure below shows a timeline with indications of the 3GPP releases and the availability of 5G network equipment, 5G Open-RAN equipment, 5G chipsets, 5G devices, 5G dedicated industrial devices.

Figure 2.12: 3GPP and 5G Private Networks Timeline



Source: Plum Consulting

2.3 Ecosystem and supply side

There is a well-developed and evolving ecosystem for networks and devices based on 3GPP specifications. For private networks there are differences from what is generally required for provision of public network services (although over a longer timeframe there may be some convergence). Differentiating factors might include:

- The need for higher bandwidths
- The need for lower latency with Ultra Reliable Low Latency Communication (URLLC).
- The need to support extensive IoT devices.
- Less bias toward download with applications that may be symmetrical or even uplink bandwidth biased.
- Whether networks are fully "on-site" or virtualised / provided as a service by equipment vendors, SIs or others (including MNOs).
- Whether there is a need for Mobile Access Edge Computing (MEC).

While many of these factors may not directly influence the choice of spectrum the availability of a range of devices and small cell architectures to support the user needs is important. There is a range of devices available in the n77 and n78 3GPP bands. There is a range of suppliers for devices of varying types (e.g. indoor and outdoor CPE, modems, rugged terminals, etc.) and several options for network supply.

Other issues for consideration when deploying 5G private networks include use of standalone or non-standalone networks, and practical issues such as geographic coverage requirements.

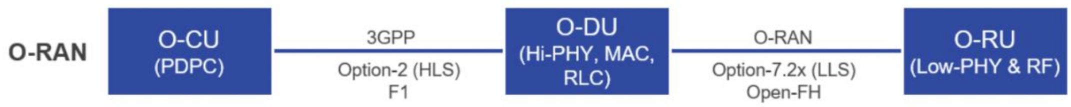
2.3.1 Mobile network equipment manufacturers

Today, more than 90% of the mobile network equipment is provided by five major manufacturers: Huawei, Ericsson, Nokia, Samsung and ZTE. With the advent of Open RAN, many newcomers have already started to grab market share. In this section, we focus on the Radio Access Network (RAN) part of the mobile equipment market and identify the main suppliers and trends for this market.

2.3.1.1 Base station suppliers

The recent trend of RAN disaggregation was initiated to enable a distributed deployment of RAN functions over the coverage area. In 3GPP's Release 15, the base station (gNB) is logically split into three entities denoted as CU (Central Unit), DU (Distributed Unit) and RRU (Remote Radio Unit) as shown in the figure below:

Figure 2.13: 5G functional split options



Source: Small Cell Forum

Open RAN network specifications allow the placing of network functions in different parts of the network architecture. There are several splits[4] specified which allow tradeoffs and optimization depending on the type of network being addressed. The Option-7.2 split was selected by the O-RAN Alliance and corresponds to the interface between the RU and the DU. The Small Cell Forum choice is Option-6, with a split within the DU and Option-2 corresponds to a split between the DU and the CU.

- The Remote Radio Unit (RRU) hosts the functions below split 7 as well as all the RF processing
- The CU (Central Unit) hosts the RAN functions above split 2
- The Distributed Unit (DU) runs functions below split 2 and above split 7

The following table presents the main manufacturers present on the Radio Unit market, the Distributed Unit market, the small cell market, and the RAN (Radio Access Network) market.

- Small cell: a small cell generally has embedded antennas and comprises the RU, DU and CU in one box.
- RAN: the Radio Access Network comprises the Radio Unit, the Distributed Unit and the Central Unit. This category comprises both small cells and macro cells.

Figure 2.14: RAN equipment manufacturers (non-exhaustive list)

RAN part	Manufacturers	4G/5G private networks	Open RAN (Y/N)
Remote radio unit*	AceAxis	Y	N
	Airrays (Xilinx)	Y	Y
	AW2S	Y	N
	Celestia	Y	N
	CommAgility	Y	Y
	Commscope	Y	Y
	Filtronic	Y	N
	Gigaterra	Y	N
	MTI	Y (RF modules)	N
	NTS	Y	N
	SRS	Y	?
Distributed unit	CommAgility	Y (development p/f)	Y
	Dell	Y	Y
	HPE	Y	Y
	Kontron	Y	Y
	Supermicro	Y	Y
Small cells	Altiostar	Y	Y
	Baicells	only 4G	Y

[4] A split corresponds to the distribution of the various functions of the base station between the entities.

RAN part	Manufacturers	4G/5G private networks	Open RAN (Y/N)
	Benetel	Y	N
	Comba	Y	N
	Mavenir (IP Access)	Y	Y
	Sercomm	Y	N
“Full” Radio Access Network	Airspan	Y	Y
	Ericsson	Y	N
	Huawei	Y	N
	Fujitsu	Y	Y
	NEC	Y	Y
	Nokia	Y	Y
	Parallel Wireless**	Y	Y
	Samsung	Y	Y
	ZTE	Y	N

Notes: *: including active antenna systems; **: integrates RRH from third parties

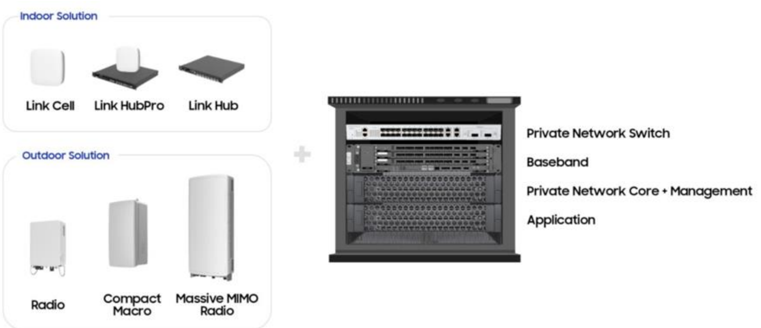
Source: Plum

The following network vendors provide small cells usable for 5G private networks:

- “Incumbent” vendors: Nokia, Ericsson, Samsung, Huawei and ZTE today control more than 95% of the global mobile network market. (For MNOs, private networks, neutral hosts and Fixed Wireless Access).
- New entrants (e.g. in the Open RAN area) such as Altiostar, Mavenir, Parallel Wireless, Airspan and Radisys.
- Other suppliers of network components such as Cisco, Fujitsu, NEC or Commscope.

Some vendors have dedicated private 5G solutions as shown in the figure below for Samsung:

Figure 2.15: Samsung’s Private 5G Solution



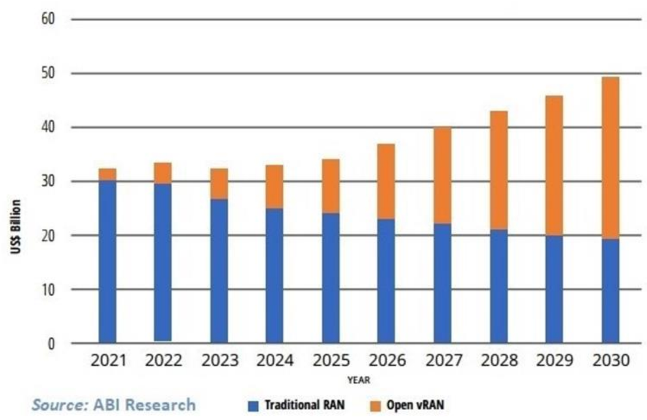
Source: Samsung

It is important for small cell vendors to understand if the market will be large enough in a dedicated country and if there will be additional requirements in terms of adjacent bands protection. Real neutral R&D expertise would be needed to be able to make decisions.

2.3.1.2 Open RAN

Open RAN is a subset of the RAN market with new entrants providing elements of the whole RAN. Open RAN equipment is suitable for private networks deployment. The three main suppliers in the Open RAN market today are NEC, Samsung, and Fujitsu according to Dell'Oro Group and it is estimated that 200,000 Open RAN base stations will be shipped in 2022 (source Joe Madden).

Figure 2.16: Revenue forecast for RAN and Open RAN



Source: ABI Research

2.3.1.3 C-band support (n77 and/or n78)

Vendors do not always publish information about frequency bands supported by their RF network equipment. We requested information from some vendors and indicate in the table below the main characteristics of small cells suitable for indoor and outdoor 5G private network deployment.

Figure 2.17: 5G small cells main characteristics

Vendor	Product	Frequency band	Configuration	Deployment type	Channel BW	Antenna	Power
Airspan	AirSpeed 2200	Sub-6 GHz	Dual/single sector	Outdoor	150 MHz	Integrated/ External	
Airspan	AirVelocity 1900	Sub-6 GHz	4T4R	Indoor	100 MHz	Integrated	2x250 mW
Benetel	5G-O-RU* RAN 550	n78 (3300-3800MHz) n77u (3700-4200MHz) n79 (4400-5000MHz)	4T4R	Indoor	100 MHz	Integrated	Up to 24dBm (at antenna port)

Vendor	Product	Frequency band	Configuration	Deployment type	Channel BW	Antenna	Power
Comba	Open Platform Small Cell DP	n78	n/a	Indoor	50/60/80/100 MHz	Integrated	n/a
Fujitsu	RU	Sub 6 Band: 600 MHz – 5.0 GHz	4TRX – 64TRX	n/a	n/a	n/a	n/a
Mavenir	E511	n78	n/a	n/a	n/a	n/a	n/a
Samsung	Link Cell	CBRS, n79, n257	n/a	Indoor	100 MHz	Integrated	n/a
STL	Garuda	n78	1 CC, 4T4R	Indoor RU	100 MHz	Omni	4x 250mW

Legend: BW: bandwidth; n/a: not available; *: Open RAN support (split 7.2)

Source: Plum Consulting

2.3.2 Chipset manufacturers

2.3.2.1 Tier-one chipset manufacturers

Qualcomm, Mediatek and Broadcom are the leaders in the 5G smartphone market today. Qualcomm and Mediatek are the leaders in the smartphone chipset market. Broadcom provides custom RF front end module (FEM) devices for mobile wireless applications.

In 2021, some chipset manufacturers started to develop 5G products for other devices such as CPE (Customer Premises Equipment) for fixed wireless access such as MediaTek T750, industrial modules (Qualcomm 315), PC modules (MediaTek T700).

In the Open-RAN market, various chipsets are used in 5G base stations for the RF functions and the broadband treatment. The latter allows the use of off-the-shelf hardware using non-specialized chipsets provided by Intel, ADI, Marvell and Nvidia – as well as in-house developments from Nokia, Ericsson and Huawei.

2.3.2.2 Tier-two and three

Many tier-two chipset manufacturers such as Infineon, Sequans or Qorvo provide chipsets for IoT applications and modules. Availability of cheap chipsets for IIoT seems to be limited today for 5G. Qorvo offers RF components such as 5G Infrastructure Front End Modules covering frequency bands up to 5 GHz.

2.3.2.3 C-band support by chipset manufacturers

C-Band support for 3GPP Release 16 started in 2021 when major chipset manufacturers such as MediaTek (M80/T800), Qualcomm (x62/65) or UNISOC (V516) released modems able to support this frequency range.

In October 2022, it seems that Qualcomm' chipsets do not support 5G for the US CBRS band. This is likely to be implemented in upcoming versions of their chipset for the US market.

In October 2022, Sequans, does not appear to provide chipsets or modules supporting the n77 or n78 bands.

2.3.3 Device manufacturers

2.3.3.1 Market status

Hundreds of 4G devices are available for the C-band today but there are less 5G devices on the market. Airspan indicated that in the USA, it is easier today to get 4G devices for the CBRS band than 5G devices and that the performances are the same due to the constraints linked to Qualcomm' chipsets. According to Nokia, "For 4.9G/LTE, there is a very developed industrial ecosystem with over 6,800 LTE-enabled non-phone-form factor devices".

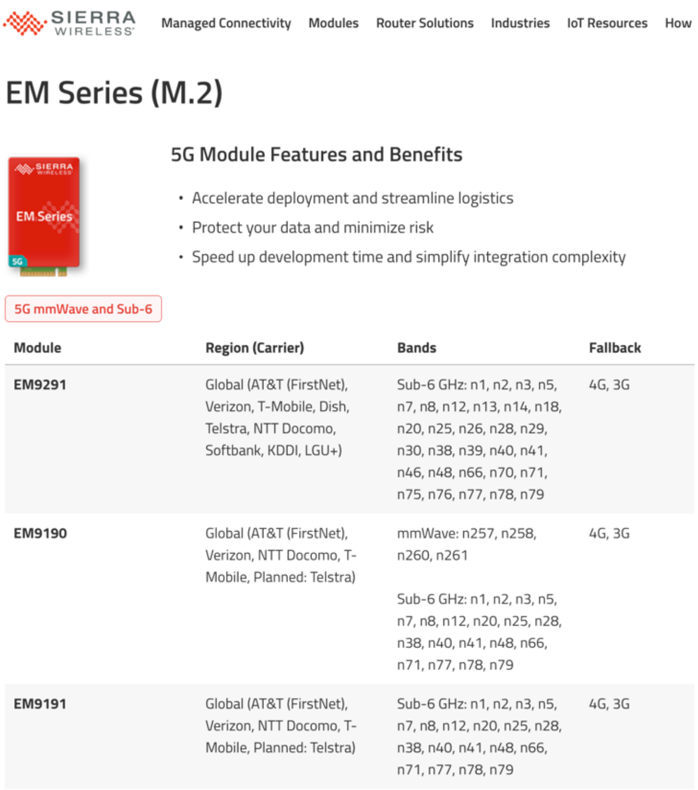
In order to provide devices together with the infrastructure for private mobile networks, Nokia works with partners such as Savox, that brings ruggedized LTE and 5G devices for industrial environments.

2.3.3.2 Dedicated devices and modules availability for 4G/5G private network users

Radio Frequency (RF) module suppliers, integrate 5G chipsets onto dedicated modules for IoT applications. 5G modules can be integrated into devices and for various industrial applications such as Industrial Router, Industrial personal digital assistant, Rugged Tablet PC and Digital Signage. Players in this field include AW2S, Comba, KRW, MTI, Quectel, Sierra Wireless, Telit…

- Sierra Wireless is an example of a device vendor supporting the C-band with 5G modules covering n77, n78 and n79 frequency bands. It seems that these modules are mainly targeting the Asian and US markets.

Figure 2.18: Sierra Wireless 5G modules


Managed Connectivity Modules Router Solutions Industries IoT Resources How

EM Series (M.2)

5G Module Features and Benefits

- Accelerate deployment and streamline logistics
- Protect your data and minimize risk
- Speed up development time and simplify integration complexity

5G mmWave and Sub-6

Module	Region (Carrier)	Bands	Fallback
EM9291	Global (AT&T (FirstNet), Verizon, T-Mobile, Dish, Telstra, NTT Docomo, Softbank, KDDI, LGU+)	Sub-6 GHz: n1, n2, n3, n5, n7, n8, n12, n13, n14, n18, n20, n25, n26, n28, n29, n30, n38, n39, n40, n41, n46, n48, n66, n70, n71, n75, n76, n77, n78, n79	4G, 3G
EM9190	Global (AT&T (FirstNet), Verizon, NTT Docomo, T-Mobile, Planned: Telstra)	mmWave: n257, n258, n260, n261 Sub-6 GHz: n1, n2, n3, n5, n7, n8, n12, n20, n25, n28, n38, n40, n41, n48, n66, n71, n77, n78, n79	4G, 3G
EM9191	Global (AT&T (FirstNet), Verizon, NTT Docomo, T-Mobile, Planned: Telstra)	Sub-6 GHz: n1, n2, n3, n5, n7, n8, n12, n20, n25, n28, n38, n40, n41, n48, n66, n71, n77, n78, n79	4G, 3G

Source: Sierra Wireless

- Quectel: the Quectel RM510Q-GL and the 5G RM50xQ series modules incorporate Qualcomm' chipsets and support bands n77, n78 and n79. They support a wide range of eMBB and IoT applications such as industrial router, home gateway, STB, industrial laptop, consumer laptop, industrial PDA, rugged tablet PC, video surveillance and digital signage.

- Telit: the FN990Axx LTE/5G data card incorporates Qualcomm' chipsets and supports bands n77, n78 and n79. They target future-proof IoT, enterprise applications and video.

5G industrial devices

- In the USA, Sierra Wireless's EM7511 module along with several gateways have been certified for the CBRS band.

- Many vendors already provide 5G industrial devices such as routers (Advantech, HMS, Milesight, Siemens, Wlink…) or Industrial IoT modules.

Figure 2.19: Example of industrial 5G router

Source: Siemens

2.3.3.3 C-band support by device manufacturers

Major modules and device manufacturers support frequency bands n77, n78, n79. Smaller manufacturers may only support band n78.

Figure 2.20: 5G industrial devices main characteristics

Vendor	Product	Type	Frequency bands	Mobile/ Fixed	NSA/SA support	Carriers/Vendors validation/certification
Advantech	ICR-4453	Router	n77/n78/n79	Fixed	Yes	Deutsche Telekom, AT&T, FirstNet, T-Mobile, Verizon (planned), Telstra
HMS	5G Starterkit	Router	n78 (other bands on request)	Fixed	Yes	T-Mobile/tested and verified in collaboration with Ericsson
Milesight	UR75-5G	Router	n77, n78, n79	Fixed		
Quectel	RG500Q-EA	IoT module	n77, n78, n79	Mobile	Yes	Many MNOs

Vendor	Product	Type	Frequency bands	Mobile/ Fixed	NSA/SA support	Carriers/Vendors validation/certification
Siemens	SCALANCE MUM853-1 5G router (EU)	Router	NSA: n77, n78,n79 SA: n77, n78	Fixed	Yes	
Sierra Wireless	EM Series (M.2)	IoT module	n77, n78, n79	Mobile	Yes	Many MNOs
WLINK	G930 Industrial 5G Router	Router	n77/n78/n79	Fixed	Yes	n/a

Source: Plum Consulting

2.4 Base station and device options and limitations

In this sub-section, we discuss how equipment can cope with additional constraints such as protection of adjacent bands.

2.4.1 5G base stations

There are more constraints on base stations than on devices as the former manage the radio link and the device power level. Learnings from the interviews are the following:

- Antenna systems: 2x2 or 4x4 antenna configurations are available for most indoor small cells available on the European market. Massive MIMO configurations provided for macro base stations are not well suited to 5G private networks as the radiated power can exceed reasonable limits in certain areas of the coverage zone.

- Adjacent band protection beyond 3GPP specifications & ability to effectively handle specific restrictions for out-of-band emissions (ability to add/change filtering profiles). The 5G base stations adapt to their environment (power level) but it is expected that many small cell manufacturers will not do any dedicated development (add a filter for instance) if there is a specific national regulation on top of European regulations or to meet stringent out of band emissions.

- Carrier aggregation between 3.4-3.5 GHz or 3.7-3.8 GHz and a potential future allocation in 3.8-4.2 GHz for localised networks: Airspan recently discussed with EUWENA (European Users Wireless Enterprise Network Association) on the same topic and answered that it is mainly an issue for 5G devices and thus a question for chipset and device manufacturers. While technically possible the ability in practice to aggregate the 3.4-3.5 GHz band with the 3.8-4.2 GHz band will depend on equipment vendor development choices (i.e. do they see demand for the additional complexity that might be involved)..

- In the 3.8-4.2 GHz band, the UK set up a dedicated spectrum mask which would have obliged Airspan to add an external cavity filter. Due to the mechanical and costs constraints this implies, Airspan decided not to address this market. Other vendors have addressed this market including incumbent vendors such as Nokia, Huawei or ZTE as base stations able to support such additional constraints.

- ✂

- ✂

2.4.2 5G chipsets and devices

2.4.2.1 Chipsets

✂

2.4.2.2 Devices

Airspan underlines that in the USA, it is easier today to get 4G devices for the CBRS band than 5G devices and that the performances are the same due to the constraints linked to Qualcomm' chipsets. Apple's new iPhones support CBRS, and Sierra Wireless's EM7511 module along with several gateways have been certified for CBRS.

5G Routers are already sold by Siemens. Larger availability of 5G devices for industrial environments in Europe is expected for 2023. A majority of 5G devices that are coming to the European market support band n77 (3.3-4.2 GHz).

✂

3 Spectrum options

3.1 Introduction

This section considers options to provide spectrum to 5G private networks and constraints that might apply. It considers the proposal to use a spectrum reservation at 3.4-3.5 GHz in the Netherlands and makes comparisons to use of 3.7-3.8 GHz as used in Germany.

In order to consider the characteristics of a spectrum reservation it is important to consider where it sits in the 3.4-3.8 GHz band and what current use and potential future use of adjacent spectrum might be.

Figure 3.1: 3.1-4.2 GHz

3100-3400 MHz Radiolocation (primary)	3400-3800 MHz Harmonised for electronic communication services (3600-3800 MHz fixed satellite space to earth and fixed service – both primary)	3800-4200 MHz Fixed satellite space to earth and fixed service – both primary

- In the spectrum below 3.4 GHz the key service deployed is radiolocation. This is primarily shipborne radar systems, which require protection from harmful interference originating in band and in adjacent bands. Specific requirements are specified for this in the European Union Implementing Decisions for the 3.4-3.8 GHz band. There are no changes foreseen to use of 3.1-3.4 GHz and the need to protect services using the band will continue. The block edge mask requirements for protection of the radiolocation service apply nationwide in the Netherlands and are applicable to the deployment of mobile services (public or private) in spectrum above 3.4 GHz. The implications of the protection requirements are discussed later in this chapter

- In 3.4-3.8 GHz, which is harmonised for electronic communication services, the main service requiring protection is ground stations of the Fixed Satellite Service (FSS) when the administration deems this necessary. There are several ways in which protection can be delivered including physical shielding of the FSS stations, not assigning certain frequencies to mobile services in the proximity of FSS ground stations, reduction of transmitter powers and imposing isolation zones around satellite ground stations. The precise protection measures to apply will be determined by administrations.

- The spectrum above 3.8 GHz is mainly used by FSS ground stations and again protection of these will depend on the policy applied by the administration. The future use of spectrum in the frequency range 3.8-4.2 GHz is being considered by the European Commission, which has issued a mandate to CEPT[5] on technical conditions for shared use of the band for local area network connectivity. The timetable for this activity concludes in March 2024 with a final report to the European Commission. It is anticipated that, depending on the outcome of the CEPT work and associated consultation, that the Commission will move to an Implementing Decision on shared use of the band. It is important when considering the choice of spectrum for private networks that the potential future allocation of 3.8-4.2 GHz is taken into account.

[5] Mandate to CEPT on technical conditions regarding the shared use of the 3.8-4.2 GHz frequency band for terrestrial wireless broadband systems providing local area network connectivity in the Union. 16 December 2021.

3.2 Status of 3.4-3.8 GHz spectrum

The 3.4-3.8 GHz band is key for deployment of 5G infrastructure and services within the European Union. There are several instruments applying to its use:

- Implementing Decision (EU) 2019/235[6] - this is the most recent Implementing Decision regarding the band. It modifies Decision (EU) 2008/411/EC[7] which itself was modified by (EU) 2014/276. The changes to the Decision update relevant technical conditions with the advance of technology toward 5G and the adoption of TDD technology for the band (the earlier Decisions permitted a mix of FDD and TDD). A key part of the Decisions is the definition of Block Edge Masks (BEMs) that apply to base station equipment operating in the band.
  - The Radiolocation service operating in 3.1-3.4 GHz is a specific case covered by Decision EU (2008)/411/EC where EU countries with military radiolocation systems operating below 3400 MHz (two cases are specified) can decide whether to use an EIRP limit of -59dBm/MHz or -50 dBm/MHz (for non-active antenna systems). Administrations can also set a guard band below 3.4 GHz in which case the power limit applies below the guard band. In the case of active antenna systems for Case A the limit is -52dBm/MHz/cell (TRP).[8]

Figure 3.2: Base station additional baseline power limits for country specific cases

Case		BEM element	Frequency range	Power limit
A	Union countries with military radiolocation systems below 3 400 MHz	Additional Baseline	Below 3 400 MHz for both TDD and FDD designation	– 59 dBm/MHz EIRP
B	Union countries with military radiolocation systems below 3 400 MHz	Additional Baseline	Below 3 400 MHz for both TDD and FDD designation	– 50 dBm/MHz EIRP
C	Union countries without adjacent band usage or with usage that does not need extra protection	Additional Baseline	Below 3 400 MHz for both TDD and FDD designation	Not applicable

Source: European Commission

- The 3.4-3.8 GHz band has been assigned to operators in most of the European Union. In many instances all spectrum available in the band has been assigned to mobile network operators (MNOs).[9] In Germany, 300 MHz was assigned to MNOs and 100 MHz was reserved (3.7-3.8 GHz) for the provision of local usage. Bundesnetzagentur has set out guidance for the use of this 100 MHz.[10] Sweden, made 3760-3800 MHz available for local private network use in 2021 (indoor and outdoor). So far Germany and Sweden are the only countries in Europe to make reservations for mobile private networks within the 3.4-3.8 GHz band. Otherwise, mid-band spectrum in the frequency range 3.4-3.8 GHz is generally being made available for these networks via leasing obligations rather than specific frequency allocations.

[6] Commission Implementing Decision (EU) 2019/235 of 24 January 2019 on amending Decision 2008/411/EC as regards an update of relevant technical conditions applicable to the 3 400-3 800 MHz frequency band.
[7] Commission Decision of 21 May 2008 on the harmonisation of the 3 400-3 800 MHz frequency band for terrestrial systems capable of providing electronic communications services in the Community.
[8] Annex 1 to the implementing Decision specifies that alternative measures may be required on a case by case basis for indoor AAS base stations on a national basis and that in a multi-sector base station, the radiated power limit applies to each one of the individual sectors
[9] In some cases the assignments avoid the bottom of the band and have, for example, left 10 MHz of the band unoccupied to provide protection in services below 3400 MHz.
[10] Administrative rules for spectrum assignments for local spectrum usages in the 3700-3800 MHz band (Administrative rules for local broadband applications). Bundesnetzagentur 01 December 2021.

3.3 Spectrum for private networks

There are several factors that influence the choice of spectrum for mobile private networks. Ultimately spectrum demand will be driven by the characteristics of the applications supported on private networks, which could include mobile broadband, sensors, control equipment, with some use cases being mission critical. Applications could be used indoors and/or outdoors and be static, nomadic or mobile. A key trend potentially influencing spectrum demand is the move from devices that are often voice and/or low data rate sensors and controllers to more sophisticated broadband devices providing more complex and extensive information and control functions (in both uplink and downlink).

To assess spectrum needs applications can be characterised by considering:

- QoS – This refers to the application's requirement in terms of the network speed and consistency as well as requirements on latency and resilience. High QoS is needed for applications that are mission-critical. High QoS requires a predictable spectrum environment.

- Coverage level – This relates to the setting in which the application is deployed as well as requirements for mobility. Industrial applications can include the use of wireless connectivity in wide outdoor areas such as on large farms or in indoor spaces such as storage facilities. Lower frequencies may favour longer range applications.

- Bandwidth – Bandwidth requirements refer to the throughput level necessary to enable the application(s) to operate. Some applications (e.g. virtual reality) not only require high QoS but also very high data transmission rates.

- Symmetry – Consumer focused mobile networks are downlink biased. However, in some applications, the relative amounts of bandwidth required for uplink and downlink transmissions differ. Applications that are based on high-definition video monitoring, for example, will require a very high bandwidth in the uplink direction.

Most private and industrial network environments require a mix of the above. Mid-band spectrum generally provides a good compromise to deliver services but in some very dense traffic use environments there may be a need for mmWave spectrum.

Spectrum for mobile private networks can be accessed via several means:

- Provide the network using spectrum licensed to an MNO. This could include:
  - An MNO directly providing the private network via its existing network footprint and/or addition of infrastructure to meet the private network's requirements.
  - Through trading or leasing of MNO spectrum to the entity providing the private network. While this is possible there are relatively few examples of such transfers to date. The ability to transfer spectrum on a subnational basis is required for this approach to work. There are leasing / sub-licensing arrangements specified for industry verticals in some countries (e.g. in Denmark, Finland, France)[11] for the 3.4-3.8 GHz band, which work as an alternative to a reservation / set-aside but it is not clear what demand has emerged so far.

[11] Spectrum leasing in the 5G era. GSMA January 2022,

- Via advanced spectrum sharing mechanisms (e.g. dynamic spectrum access). Aside from the deployment of the Citizens' Broadband Radio Service (CBRS) in the United States there are few operational examples of this approach at these frequencies.

- Provide the network from spectrum dedicated for provision of private networks:
  - This approach has been applied in Germany and Sweden for spectrum in the 3.7-3.8 GHz band (see above).
  - A similar approach has been applied in the UK since 2019 in 3.8-4.2 GHz for low and medium power local networks. France has adopted 3.8-4.0 GHz for this purpose since March 2022.

The table below summarises our understanding of the way in which spectrum for private networks is being made available in European countries.

Figure 3.3: Spectrum for private networks in the 3400-4200 MHz range

Country	Band	Conditions
Belgium	3.8-4.2 GHz	Belgium is planning to reserve the band for 5G private networks
Czechia	3.4–3.6 GHz	20 MHz blocks won by O2 and CentroNet were attached to the obligation of leasing frequencies to support Industry 4.0
Denmark	3740–3800 MHz	Portion of spectrum acquired by TT-Network and subject to an obligation to lease locally to enterprises and public institutions for private networks
Finland	3410-3800 MHz	The band was allocated to the MNOs with a leasing option from private networks
France	3.8-4.0 GHz	Available for private networks until the end of 2022
Germany	3.7-3.8 GHz	Reserved for the provision of local usage
Norway	3.8-4.2 GHz	Free 3.8-4.2 GHz private network test licenses for businesses (in 2022)
Sweden	3760 - 3800 MHz	Available for local outdoor and indoor use, minimum frequency block of 10 MHz with steps of 10 MHz to a maximum of 40 MHz
UK	3.8-4.2 GHz	Available for private networks

Source: Plum Consulting

There are multiple factors that might influence the choice of spectrum access method for a business wanting to implement a mobile private network. These include the coverage, capacity, quality of service and resilience the network is required to deliver (as mentioned above) and whether or not an MNO solution is able to meet the requirements. Also of importance are cost and the ability of the business wanting to procure the network to implement and integrate the solution.

3.4 Equipment for private networks

Harmonised standards exist for equipment that will be deployed in the 3.4-3.8 GHz band. On the assumption that 5G is deployed the key equipment standard is for 3GPP frequency band n77. This covers the frequency range 3.3-4.2 GHz. Band n78 covers a subset of n77 (3.3-3.8 GHz). The standards support several carrier bandwidths:

- For frequencies in the category "FR1" sub-6 GHz carrier bandwidths range from 5-100 MHz.

- Carriers can be aggregated to support wider channel bandwidths up to 60, 200 or 300 MHz using combinations of two or three carriers.[12]

Aspects of equipment for private networks have been considered in detail in Section 2. Three key issues to address from a spectrum management perspective are:

- The need to protect in-band or adjacent band users. Requirements for this are usually specified for base stations as they control operation of the radio resource and usually operate at higher power levels than the devices connected to them.

- The physical implementation of base station equipment and the flexibility it allows for adaption to specific circumstances. For example is the equipment modular and antenna and other RF components fully integrated or can adaptions be made to add extra filtering or change antennas / their characteristics?

- The ability to make use of spectrum in the full n77 band frequency range if 3.8-4.2 GHz subsequently becomes available for private network use.

3.5 Examples of private network approaches

Two cases are considered for this report – Germany with 3.7-3.8 GHz and the UK with 3.8-4.2 GHz.

3.5.1 Germany

The 3.7-3.8 GHz band was made available for local networks in 2019 and Bundesnetzagentur has set out administrative rules for its use (which can include private networks for industry and other purposes). Key points covered include:

- Spectrum will be assigned on a technology neutral basis in multiples of 10 MHz. No guard bands will be defined and only TDD usage is possible. There is no requirement for synchronised network operation but where adjacent networks are not synchronised there may be a requirement for a guard band to be applied by the spectrum users.

- Spectrum users are permitted a relatively free hand in terms of planning their networks and Bundesnetzagentur does not generally define a maximum permissible field strength at the edge of the assignment area. However, users are required to operate in a way that does not cause harmful interference to other networks and are encouraged to use low transmit powers, low antenna heights and directional antennas.

- Geographically adjacent networks are required to negotiate coexistence and it is assumed that they will find appropriate solutions. There is a requirement for operators to submit agreements in this respect to Bundesnetzagentur. In the event of agreement between geographically adjacent operators not being achieved Bundesnetzagentur will define a field strength limit of 32 dBµV/m/5 MHz at a height of 3 metres at the border of the assignment area.

- At the application stage details submitted by local network spectrum users will be used to assess compatibility for coexistence with incumbent spectrum users. No interference may be caused to

[12] 3GPP TSG-RAN TS 38.101-1 User Equipment (UE) radio transmission and reception; Version 17.4.0

coordinated FSS ground stations in an assignment area. Other coordinated installations in Germany include:

  - Geodetic Observatory Wettzell.
  - Leeheim monitoring earth station.
  - Radio monitoring stations of the Bundesnetzagentur's radio monitoring and inspection service.
  - Radio stations in border areas.

- Bundesnetzagentur has defined block edge masks for non-active and active antenna systems operating in 3700-3800 MHz. These parameters match those set out in the Annex to Commission Implementing Decision (EU) 2019/235.

As of September 2022 Bundesnetzagentur reported that 249 applications had been made for local licences in the 3.7-3.8 GHz band and of these 243 authorisations had been granted. The types of entities granted licences include industrial, media, automotive, universities and research institutes.

3.5.2 United Kingdom

In the UK Ofcom has made spectrum available on shared basis in the 3.8-4.2 GHz band for the provision of local networks. This spectrum is available under Ofcom’s Shared Access Licence regime which in addition to this frequency band also covers 1.8 GHz, 2.3 GHz and the lower part of 26 GHz (24.24-26.5 GHz).[13]

Ofcom has set out guidelines for use of the 3.8-4.2 GHz band.[14] Key points covered include:

- The purpose of licences granted in 3.8-4.2 GHz is for provision of localised networks. It is not permitted to provide national mobile services using this spectrum.
- Two licence types are made available:
  - Low power permitting the spectrum users to deploy as many base stations as required within a circular area with radius 50 metres. It is possible to apply for multiple low power licences to cover larger areas (contiguous or spaced out). Indoor and indoor/outdoor licensing options are available. Maximum permitted EIRP 24 dBm.
  - Medium power suitable for larger coverage areas authorising a single base station generally deployed in rural areas. Maximum permitted EIRP 42 dBm.
- There are restrictions on applications within 5km of some sensitive installations.
- Ofcom has indicated that in future it might implement a dynamic spectrum access approach in the shared access bands and that it may, from time to time, request users to change their transmission frequencies.
- Technical conditions for low power licences include:

[13] Note that Ofcom has yet to finalise its approach to award of spectrum in the 26 GHz band, See Enabling mmWave spectrum for new uses. Ofcom consultation 09 May 2022.
[14] Ofcom Shared Access Licence Guidance Document. Updated 20 September 2022.

- Outdoor antennas limited to 10m above ground level.
- Authorised bandwidths of 10, 20, 30, 40, 50, 60, 80 and 100 MHz.
- Base station: 24 dBm / carrier for carriers of ≤20 MHz or 18 dBm/5 MHz for carriers of > 20MHz (EIRP).
- Terminal: 28 dBm (including a 2dB tolerance).
- Ofcom has defined out of band channel emission limits based on its analysis of relevant ECC Reports.[15] Industry concerns have been raised how the block edge masks specified by Ofcom might align with the work being undertaken by CEPT in response to the Mandate on 3.8-4.2 GHz.
- There is no frame structure requirement but Ofcom has reserved the right to mandate this later if required.

- Technical conditions for medium power licences are identical to those for low power licences except for:
  - No specification on antenna height (aside from normal planning limits applied).
  - Base station: 42 dBm / carrier for carriers of ≤ 20 MHz or 36 dBm/5 MHz for carriers >20 MHz (EIRP).
  - Terminal 28 dBm (including a 2 dB tolerance).

As of end October 2022 Ofcom's Wireless Telegraphy Register showed for the 3.8-4.2 GHz band:

- 184 low power licences issued to 42 users. The types of entities granted licences include municipalities, 3rd party network builders / operators, industrial, media, universities and research institutes.
- 408 medium power licences issued to 27 users. The types of entities granted licences are similar to those mentioned above and include public network operators (using the spectrum for non-public network purposes).

Plum carried out work for the UK Spectrum Policy Forum toward the end of 2021 that considered practical difficulties with operation of the Shared Access Licence. Key feedback included:

- Whether coexistence and protection criteria are too restrictive?
- Determination of options to site masts in relation to existing sites.
- Maximum permissible height of antennas at a specific location.
- Calculation of maximum permissible power levels at a specific location.
- The use of omni-directional antennas and the inability to handle multi-sector cells, directional antennas and MIMO/beam forming.
- The need for more thought on handling indoor use cases and whether Low Power Indoor (LPI) and/or Very Low Power (VLP) regimes could be considered.

[15] See Ofcom's consultation: Enabling opportunities for innovation – shared access to spectrum supporting mobile technology December 2018 – Annex 5 and resulting Statement published July 2019. ECC reports referred to include Reports 203, 281, and 296.

These are all examples of issues needing consideration when defining the private networks regime for the Netherlands.

3.6 Issues for spectrum reservation for private networks

The currently identified option to support a spectrum reservation for private networks in the Netherlands is 3400-3500 MHz. This has been reviewed in this study from the perspective of:

- Interference to other services, and
- Carrier aggregation with spectrum in the frequency range 3.8-4.2 GHz should this band be subsequently harmonised for provision of private networks.

We also compare 3.4-3.5 GHz with the 3.7-3.8 GHz allocation enacted in Germany.

3.6.1 Interference to other services

The table below summarises the potential coexistence scenarios.

Figure 3.4: Coexistence scenarios

Frequency option	Adoption by other countries for local networks	Likely in-band coexistence cases	Adjacent band coexistence cases
3.4-3.5 GHz	None	- Fixed Service - Fixed Satellite Service	- Radiolocation (<3400 MHz) - Fixed Service - Fixed Satellite Service - Mobile
3.7-3.8 GHz	Germany (3.7-3.8 GHz) and Sweden (3760-3800 MHz)	- Fixed Service - Fixed Satellite Service	- Fixed Service - Fixed Satellite Service - Mobile - Possible localised mobile private networks in future

Source Plum and other public documents – note that FS and FSS GS are not deployed in 3.4-3.5 GHz or 3.7-3.8 GHz in the Netherlands.

Sharing between mobile networks, the fixed service and the fixed satellite service is well understood and manageable (especially when transmitter powers employed in private networks are lower than those used on macro cells by MNOs). However, operating adjacent to the radiolocation service is more problematic. There are several approaches to resolving this:

- Provide a guard band above 3400 MHz (e.g. 10 or 20 MHz). This would apply nationwide in the Netherlands as the BEM[16] applies to the whole of the country. The application of the BEM nationwide limits the utility of private networks by reducing the overall amount of bandwidth available at all locations. There may also still be a need for filtering to be applied to base stations operating low down in the band (i.e. just above the guard band).

[16] Block Edge Mask (BEM) correspond to a regulatory approach for the definition of a set of "common and minimal (least restrictive) technical conditions" optimised for, but not limited to, fixed/mobile communications networks (source: CEPT). A BEM is a transmitter spectrum mask that applies at the edge of a contiguous licensed block of spectrum and is designed to offer sufficient protection from interference to any anticipated receiving system in an adjacent frequency block (source: telecomabs.com).

- Reduce transmit power to very low levels for frequencies near to the band edge (or restrict use to indoor only). This may reduce the coverage provided by private networks and lead to deployment of more infrastructure to cover the same area. However a greater number of transmit stations in an area may still require aggregate effects to be considered for interference.

- Modify the RF transmit chain to include additional filtering that will meet the block edge mask requirement specified in Decision 2008/411 (EC). While in theory this approach can deliver the protection required, in practice its implementation depends on whether the equipment is able to be modified and the willingness of the vendor to do this. If it is not possible to modify the equipment then it will not meet the requirement and cannot be used Provision of such filtering capability on MIMO and/or active antenna systems might also be expensive and problematic. Key considerations to implement protection through additional filtering are:

  – The form factor of the equipment. Radio units for macro cell and larger base station implementations may be able to accommodate the additional equipment more easily (e.g. provision of cavity filters, modification to diplexers / other parts of the transmit/receive chain), although this will be more difficult and costly for active antenna systems. Small cell implementations may have less flexibility due to their form factor and space budgets.

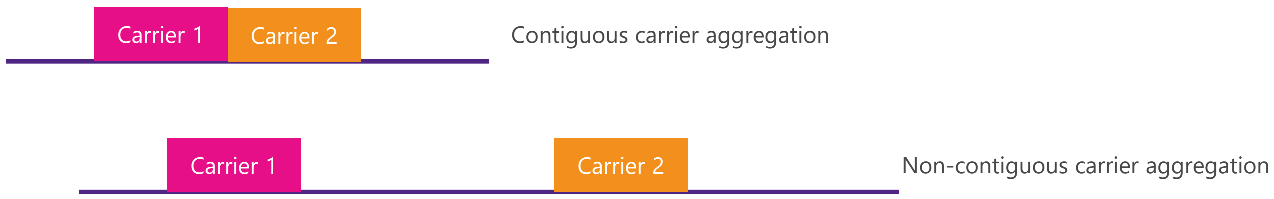
  – There will be design and testing costs to develop the implementation to meet the block edge mask requirements. Without sufficient scale these could result in price rises to radio units that manufacturers do not consider viable.

  – There will be additional costs resulting from obtaining type approval for the modified equipment. Again these might not be viable in the absence of sufficient scale of deployment.

3.6.2 Carrier aggregation

While carrier aggregation of two or three carriers is specified by 3GPP for bands n77 and n78 there may be practical issues with implementation. Ideally for intra-band aggregation contiguous carriers deliver best performance (intra-band contiguous carrier aggregation) as the configuration can be handled by a single RF transceiver. If this is not possible and there is a gap between the component carriers an RF configuration that supports two or more RF channels is required (non-contiguous intra-band carrier aggregation).

Figure 3.5: Contiguous and non-contiguous carrier aggregation



Source: Plum

The number of transceivers in equipment (e.g. small cell or user device) is likely to depend on the application and its price point. We expect to see a range of devices emerge over time and that some of these will be simple single transceiver designs with others being more complex and supporting higher bandwidths and greater functionality – in practice the simpler designs are likely to meet many user needs for mobile private networks. Single transceiver designs will not support aggregation between 3.4-3.5 GHz carriers and spectrum above 3.8 GHz. The same may be true for spectrum in 3.7-3.8 GHz unless the carriers being aggregated are immediately adjacent and at the top of one band and the bottom of the other.

For dual (or more) transceiver equipment there are less restrictions and aggregation should be possible between carriers in spectrum above 3.8 GHz and those in both 3.4-3.5 GHz and 3.7-3.8 GHz. However there may be RF efficiency issues if carriers are several hundred MHz apart although modern antenna technology offers better linearity of performance over entire bands. Equipment vendors have suggested, especially for small form factor equipment, that there might be a sweet spot for private network equipment and carrier aggregation operating in a 300 MHz frequency range (e.g. 3.7-4.0 GHz) to maximise antenna and RF efficiency.

For aggregation within either 3.4-3.5 GHz or 3.7-3.8 GHz equipment / devices designed for band n78 can be used. To aggregate carriers between either 3.4-3.5 GHz or 3.7-3.8 GHz with carriers above 3.8 GHz, equipment supporting either 2 or 3 CA in band n77 is required.

Carrier aggregation requires additional processing, which can increase power drain. While this may not be an issue for network equipment it might be an issue for battery powered devices (especially those that are required to support long operational durations without external power) and may lead to some CA scenarios not being implemented. The uplink capacity required should also be considered.

In many public networks there is a 75%:25% downlink:uplink split based on the need for greater downlink transmission capacity to support video and other high bandwidth applications. In industrial application there may be a need for different TDD splits to accommodate more symmetrical or uplink biased services and the possible use of carrier aggregation to support enhanced uplink capability (e.g. if transmitting UHD video from a device to the network). It should be noted that the option sometimes used on public networks of using a carrier in a different band to provide additional / more robust uplink capability will not be available for standalone private 5G networks based on a single frequency band solution.

Hence, the key issue that arises for carrier aggregation in the scope of this study is with single transceiver equipment operating in the 3.4-3.5 GHz frequency range and its inability to support aggregation with carriers in the 3.8-4.2 GHz band should this become available later for mobile private networks.

4 Analysis

4.1 Why private networks need dedicated spectrum

The increasing use of automation and other cyber-physical systems for the realisation of Industry 4.0 and similar initiatives is driving a requirement for more and better wireless connectivity for factories, other industrial venues, sea and airports and similar locations. There are several ways in which mobile private networks (i.e. networks serving a non-public mobile application such as an industrial, enterprise or similar environment) can be realised. Some of these require access to spectrum on a shared basis that is not being used by MNOs or other services. In other cases, where the mobile private network is procured through an MNO, the private network can run on spectrum already assigned to the MNO.

Key questions when building a mobile private network are the coverage, capacity, quality of service and resilience it requires. If these parameters fit with what an MNO can deliver, then using an MNO service may be an option if price and other non-spectrum factors are suitable. If an MNO cannot meet the requirement, then a mobile private network may be the way forward. As set out elsewhere in this report it may be possible to lease spectrum from an MNO to enable the network, otherwise there is a need for access to spectrum to support the requirement. The type and amount of spectrum required is then a function of unserved demand.

Demand is emerging for mobile private networks. It is difficult to quantify demand where the need is served directly through an MNO as these cases are not always visible. In the case where a spectrum allocation has been made to support these networks there is evidence of emerging demand as in Germany and the UK. In Section 2 we have set out forecasts for private networks volumes.[17] If one is focusing on use of 5G it is likely that users could need bandwidths of 40 MHz or more and potentially up to 100 MHz depending on the applications supported.[18]

Without an option to access dedicated spectrum there is a risk that the development of mobile private networks will run at a slower pace, which potentially impacts innovation, productivity and international competitiveness. Reasons for this might be slower adoption of automation or smarter manufacturing techniques, reductions in quality through less good sensor and control networks, less effective human machine interaction and a reduction in flexibility resulting from the advantages wireless brings in terms of being able to reconfigure equipment and processes. Although development of the mobile private network market using dedicated spectrum is at an early stage it appears clear that networks builders value the ability to be able to access this spectrum.

4.2 Spectrum

4.2.1 Options for mobile private networks

There are several spectrum options to support mobile private networks for 5G – examples are set out below:

- The 3.4-3.8 GHz and 3.8-4.2 GHz bands are commonly identified as they offer a useable balance between capacity and coverage (given that most of these networks will cover constrained geographic areas and often be indoors). An ecosystem is developing around these frequency bands to support

[17] Note that forecasts for private networks do not distinguish between those using dedicated spectrum and those supported on spectrum assigned to MNOs.

[18] The actual bandwidth requirements for a private network are driven by the sorts of applications being supported (e.g. narrowband or broadband, the concurrent volume of devices operating in a cell. Other factors like link budget and uplink/downlink requirements can also drive the need for more spectrum.

mobile private networks and 5G specifications allow options to support effective network realisation (especially for 5G standalone networks).

- Longer term the 3.8-4.2 GHz band looks like it will be adopted for private (and other localised) networks in the European Union and this is becoming a focus for vendors and ecosystem suppliers. The band has already been adopted in the UK and 3.8-4.0 GHz is being adopted in France for test licences.
- Other licensed spectrum bands available in parts of Europe are the 1.8 GHz (e.g. UK), 2.3 GHz (e.g. Finland), 2.6 GHz (e.g. France) and 26 GHz bands (e.g. Finland, UK). Unlicensed spectrum can also be used in the 5 GHz band (e.g. with WiFi 6) and in the CBRS band (3.5 GHz) in the USA (e.g. GAA spectrum or PAL lease)[19].
- Other bands potentially identified for mobile private networks include 4.9 GHz and further mmWave frequencies.

For now the use of spectrum in the 3.4-4.2 GHz frequency range appears to be gaining the most momentum given its characteristics and its developing equipment ecosystem. With some of the other bands that might be used for mobile private networks disadvantages for support of 5G include lack of available bandwidth and suitable ecosystems.

4.2.2 Analysis of options for dedicated spectrum

Early movers have used leasing or reservation of spectrum for mobile private networks. The most prominent example of spectrum reservation (or set-aside) is in Germany at 3.7-3.8 GHz. Equipment vendors have moved to make kits available to support 5G networks in this band. Sweden has also made 3.76-3.80 GHz available for similar use.

In the Netherlands two options have been consulted on for mobile private networks and a public consultation took place in 2022 for the spectrum option 3.4-3.5 GHz (the currently identified option).

3.4-3.5 GHz is problematic for all spectrum users (public and private mobile network operators) due to protection of the radiolocation service operating in 3.1-3.4 GHz for which stringent block edge masks are specified in the EU Implementing Decision. The requirement to comply with the protection criteria is applied nationwide across the Netherlands because radar carrying platforms might be nomadic throughout the country. Mainstream equipment vendors (e.g. Ericsson, Nokia) have supplied equipment that meet the relevant criteria but we have been told during the interviews that this is challenging (technical and cost) or even prohibitive for smaller scale suppliers of 5G private network equipment.

4.2.3 Coexisting with the radio location service

Meeting the protection criteria for the radiolocation service can generally be achieved by several means:

- Shielding of radiolocation service receiver sites – not really practical given the nature of the service (radars).

[19] GAA is General Authorised Spectrum is unlicensed spectrum that users can access subject to compliance with technical conditions. PAL is Priority Access Licenses awarded to users on a localised basis. These licenses can be used to support networks (public or private) and PAL holders are also able to lease their spectrum to support other networks. See the FCC's overview https://www.fcc.gov/wireless/bureau-divisions/mobility-division/35-ghz-band/35-ghz-band-overview

- Use of isolation zones[20] around receivers. If there were relatively few of these, this approach might work. However, if they are spread out and if some are in motion / nomadic use, this approach becomes problematic due to the total area of all isolation zones and the need to possibly create temporary zones for moving receivers. The size of isolation zones depends on the parameters applied to the sharing analysis.

- In the Netherlands, the aforementioned measures are not applicable. Hence, the use of frequency separation – guard band could be considered. In some countries a guard band has been created at the top end of the radiolocation band (e.g. 10 or 20 MHz).[21] This reduces the out of band power of any transmitter likely to interfere with radiolocation receivers. However, even with guard bands other measures like reducing power within areas where radar receivers are located might still be necessary. For the Netherlands, that would imply a nationwide limitation in radiated power. Given that localised networks are likely to have base station transmit powers significantly below those of macro cells the extent of additional measures where guard bands exist might be limited.

- Use of limiting power levels as a means of protection can become more complex where active antenna systems are used (although this is less likely to be the case today with mobile private networks).

If a "generic" approach is to be taken to authorisation of private networks in spectrum close to the radiolocation service without detailed coordination of every private network – the only way in which this can be achieved is through guard bands.

According to the interviews most small cell equipment vendors are unlikely to readily support an ecosystem based on 3.4-3.5 GHz for 5G mobile private networks if they are required to implement solutions to meet the out of band block edge mask due to the costs, fabrication issues and testing / type approval required to provide such a solution, especially for one relatively small market. Also, this is a distraction for them from working on an ecosystem at higher frequencies (e.g. 3.7-4.2 GHz), which is where many are currently focusing their efforts. Note that the protection issues described largely apply to base stations rather than devices, which transmit at lower power levels (although consideration may have to be given to aggregate interference levels in some cases).

4.2.4 Implications of protection

We note that operation in 3.4-3.5 GHz is more complex close to the lower edge of the band when near to sites of the radiolocation service. For all users it creates additional costs through provision of extra filtering and potentially implementation of other mitigating measures. Application of a suitable guard band may provide sufficient mitigation with industry standard equipment but further technical analysis is required to verify whether this is achievable.

A key question is who is better able to make effective use of this spectrum and under what conditions – public mobile network operators with access to equipment that can be used in this part of the band even if it is more costly, or private network operators who may be faced with an increase in costs or reduction in available bandwidth (guard band) that might reduce the effectiveness of their business plans?

[20] An isolation zone refers to an area around a receiver where other transmissions are not allowed or are restricted to ensure that harmful interference is not being caused to the protected service.

[21] Note that this might be implemented as 10 MHz below the band edge and 10 MHz above the band edge as in the UK.

It should be noted that the supply market for mobile private networks differs from that that which serves MNOs with largely macro networks (although some players developing Open RAN and similar solutions are looking at both public and private deployments). Also for industrial and other private network players establishing workable price points for equipment/systems is vital. Suppliers in the private network market need to establish economies of scale (especially for small Radio Units), which can only be achieved by offering standardised solutions and largely limiting customisation to what is possible in software.

Hence, it is not possible to treat spectrum in the 3.4-3.5 GHz frequency range as being homogenous as there are clearly different characteristics and therefore conditions that will apply to use of the spectrum depending on proximity to the 3.4 GHz band edge.

4.3 Carrier aggregation

This report also considers options for carrier aggregation between 3.8-4.2 GHz and 3.4-3.5 GHz or 3.7-3.8 GHz.

At standards level these aggregation possibilities are achievable (intra-band carrier aggregation in 3GPP band n77) but whether they can be done in practice largely depends on the implementation of base stations and devices (chipsets and radio units). Carrier aggregation is always easier to achieve if contiguous carriers are used but this will not be so for the 3.4-3.5 GHz case and may not be so for the 3.7-3.8 GHz case. Non-contiguous carrier aggregation requires the use of two or more transceivers depending on how many non-contiguous carriers are to be aggregated. This is a design and manufacturing decision for vendors based on the applications likely to be served. We came across examples of both single and multi-transceiver equipment in our research.

A further issue raised is the ability of the RF components (especially antennas) to handle transmissions where carriers might be separated by several hundred MHz. We understand that there have been significant improvements to the linearity of antennas used in mobile systems and that while such frequency combinations might have presented problems in the past they are less likely to do so now.

Hence, the ability to aggregate carriers across the bands specified comes down to more of an equipment cost and procurement issue, rather than fundamental limitations of the technology.

5 Conclusions

In this report, we have described the status of wireless private networks around the World and analysed the associated equipment ecosystem for base stations and devices. We have evaluated spectrum options setting out the availability and constraints on use of spectrum, analysis from other administrations of provision of private networks and potential future allocations and their implications for spectrum used for private networks in the 3.4-3.8 GHz band. An analysis of this information has been provided and in particular factors driven by choice of spectrum.

Germany was the first EU country to make a frequency reservation for local networks in spectrum at 3.7-3.8 GHz. Sweden has also made spectrum available for private networks in 3.76-3.80 GHz. We could not find any relevant examples of spectrum being made available for assignment to mobile private networks at the lower end the band (3.4-3.5 GHz). Some countries are making spectrum available for private networks above 3.8 GHz including the UK (3.8-4.2 GHz) and France (3.8-4.0 GHz). Norway has made spectrum available for test licences (3.8-4.2 GHz). While it is still early in the deployment of mobile private networks, evidence of demand is emerging through frequency assignments being made in both the UK and Germany.

In addition to the specific allocations / assignments mentioned above, there are leasing / sub-licensing arrangements specified for industry verticals in some countries (e.g. in Denmark, Finland, France) for the 3400-3800 MHz band, which work as an alternative to a reservation / set-aside but it is not clear so far what demand has emerged through these arrangements.

The radiolocation service in 3.1-3.4 GHz creates a problem for operation at frequencies immediately above 3.4 GHz and several European administrations have avoided assigning the bottom 10 MHz of the 3400-3800 MHz band to protect services in the lower adjacent band. The EU Implementing Decision 2019/235 specifies clear and stringent out-of-band emission limits to protect radiolocation and allows for a 10 MHz guard band below the 3.4 GHz band edge. The most likely workable mitigation for mobile private networks lacking special/steep filtering to meet the BEM requirement is the use of a guard band above 3.4 GHz, which will reduce the amount of spectrum available for these networks but may still provide sufficient spectrum (e.g. 80 MHz). Imposition of a power limit for mobile private networks in addition to a guard band will also reduce the risk of interference (these networks are not likely to need to transmit at the powers used by macro cells in public networks). However, whether such measures will completely avoid the need to fit additional filters to private network equipment requires further investigation.

We noted a reluctance on the part of some new equipment vendors to adapt their network equipment to specific RF environments that would require modifications like additional filtering (either because these networks will be operating at the band edge or of a guard band not fully protecting adjacent services). It is difficult to modify / add additional filtering to modular small cell implementations, for example. Adaptations might also be costly (e.g. costs and mechanical issues for filters, diplexers, and other RF components for small cells). There is less pressure on device vendors.

It is still relatively early in the lifecycle of the 5G network equipment ecosystem for industry verticals and local network deployments, although activity by smaller / alternative vendors is building to compete with the larger vendors in these sectors. The device ecosystem is also developing and while there are a growing number of mainstream 5G devices operating in the band, the ecosystem for other CPE and modules is still at an early stage and will take another year or more to fully develop as demand for mobile private network equipment increases. The advent of Open RAN and its opening of more options for building networks with defined interfaces and simplified radio units may lower barriers to entry for private 5G network equipment development and production. Other ecosystem points from our research include that with CBRS 5G is not yet supported but chipsets and RF implementations are being worked on and may come to market in a 12-month window.

Generally, it is also early in the ecosystem lifecycle for 5G standalone private networks but these are coming to market and are expected to simplify the implementation of private networks over the next 12-24 months.[22]

Carrier aggregation is possible in both 3GPP bands n77 and n78. On the question of whether carriers in 3.4-3.5 GHz can be aggregated with carriers above 3.8 GHz there is a requirement that band n77 equipment / devices are used (the n78 upper limit is 3.8 GHz). For n77 aggregating across carriers below and above 3.8 GHz will require that devices support non-contiguous intra-band aggregation across the whole frequency range of band n77. From a technical perspective this is possible but realisation depends on equipment specifications implemented by vendors for the private network market.

While outside the scope of this study it is important to consider the socio-economic benefits of where the spectrum allocation for mobile private networks sits in the 3.4-3.8 GHz band. To frame this there could be different benefits from locating mobile private networks at the lower end of the band to those that would arise from location at the upper end as in Germany. Key to this in each case is to assess how benefits flowing from private 5G deployments (e.g. in harbours and industrial areas) weigh against the benefits driven by all possible end users of MNO's.

[22] The point on availability of standalone networks applies to both public and private 5G networks and the entire frequency band covered by equipment (e.g. 3GPP bands n77/n78).