Humanities and Social Science Research; Vol. 8, No. 3; 2025
ISSN 2576-3024 E-ISSN 2576-3032
https://doi.org/10.30560/hssr.v8n3p1

Adoption and Deployment of a New Major Wireless Technology: The Mobile Telephone 5G. A Provisional Overview

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Received: January 21, 2025; Accepted: March 6, 2025; Published: March 12, 2025

Abstract

This research aims to contribute to the task of explaining the factors involved in the design and the use of 5th generation mobile telephony technology by examining the constraints and conditions that determine the vertical innovation, i.e. the launch and deployment of 5th generation mobile telephony technology worldwide, with a particular focus on Europe. The ultimate objective is to build up an overview of this launch and deployment in order to make the numerous reports and studies of specialised international organisations available to the academic world - teachers but also students - and to the political decision-makers concerned. The research takes a perspective which emphasises economic and business issues as well as the strategy, a topic sometimes neglected by scholars. The text is structured in four main sections, which comprise the constraints and conditions, including technology and regulation, the way to 5G, investment, expenditure and costs, the deployment of this technology around the world and in Europe and, finally, a first approach to Europe's backwardness.

Keywords: 5G, mobile telephone, technological change, Europe's backwardness

1. Introduction

In the short time that mobile telephony has been around, researchers have been faced with a double dilemma: its early adoption in some countries and its later take-up in others, and the loss of early leadership by the pioneers in general (Massaro and Kim, 2022, pp. 1-18; GSMA, 2018) and Europe in particular (Wood and Sherrington, 2024, pp. 4-5), with several countries lacking some of the optimal conditions for this technology rollout (Blackman and Forge, 2019, pp. 22-25). Both parties are challenged with the task of explaining the factors involved in the design and the use of new major wireless technology. Europe's 5G rollout has faced unique challenges compared to other regions. What is causing Europe's slow 5G adoption? What factors are impeding Europe's ability to fully capitalize on 5G compared to other regions? Is the issue primarily technological, regulatory, or economic?

In this paper, we will dissect these factors, looking at their impact on Europe's ability to lead in 5G adoption.

This research aims to contribute to the task of explaining the factors involved in the design and the use of 5th generation mobile telephony technology by examining the constraints and conditions that determine the vertical innovation, i.e. the launch and deployment of 5th generation mobile telephony technology worldwide, with a particular focus on Europe, which is highly fragmented at the member state level and faces the Single Market for a sustainable future and prosperity within everyone's reach (Letta, 2024).

The research draws from a wide range of academic and industry reports, as well as providing citations from credible sources like the European Commission and GSMA. It should be pointed out that, despite their relevance, they are sometimes heavily criticised. For example, the European Court of Auditors (2022, p. 19) notes that information on 5G deployments in Member States' 5G strategies provided by the European Commission's 5G Observatory is not always reliable.

2. Constraints and Conditions

2.1 Technology and Regulation

5G is the more advanced stage of a journey of mobile communication, starting from the 1980s (Prasad (ed.), 2022, p. XVI). This standard represents a step change in the future of technology and communications because of the wide range of innovative uses it can support. For a series of use cases, it was predicted that the communication traffic will be beyond 1000s times higher in the 2020s than in the 2010s. It was also envisaged that 5G systems should enlarge its capacity to support this demand accordingly. In addition, ultra-high speed transmission of up to 10Gps will be needed to allow users to accede to ultra-high capacity contents. As has emerging Internet of things

(IoT) or Machine to Machine (M2M) communications indicated, massive number of objects will be starting to communicate each other sooner or later (Association for Radio Industries and Businesses, 2014).

The first mobile phones were introduced in the 1980s under the name of Advanced Mobile Phone System. It used 1G technology for analogue calls, which worked like a landline phone and suffered in various ways. The maximum achievable speed was 2.4 Kbps but international data roaming emerged. The 2G mobile technology, GSM, emerged in 1991 and reached its peak of deployment in 2015 with 3.83 billion subscribers served by over 700 operators in 219 countries and territories. It achieved digital voice, faxes and SMS (Lemstra, 2018, pp. 587-611). 3G, based on a high-speed packet access (HSPA/HSPA+) and Multiple-input Multiple-output (MIMO) for multiplying the power of the wireless network and framed into universal mobile telecommunication system (UMTS), allowed the advent of smart phones. 4G, launched in 2010 and supported by the system Long Term Evolution (LTE) and WiMAX technologies, was purely mobile broadband standard. It permitted faster mobile broadband and then video viewing, videoconferencing and GPS (KPMG, 2019, p. 10; Dangi et al., 2021, p. 1; Gobierno de España, 2020) (Note 1).

Since 2012, many European countries had a rapid adoption of 4G services. At the end of 2017, the 285 million 4G connections in the region accounted for 42% of total connections. 85% of the population in Europe subscribed to mobile services (GSM Association, 2018).

Even with the differences between the first four successive generations of mobile network technology, many actions or attributes are part of a recurring pattern in terms of succession: a new generation is on the way every decade. The 5G rollout largely followed the expected timeline, with initial advancements taking place around 2020. Interestingly, the early phases of mobile technology adoption were led by state-owned monopolies. In contrast, the more recent generations have been driven by open market competition (Lemstra, Cave and Bourreau, 2017, pp. 22-23) (Note 2).

5G provides a high data rate, ultra-reliable low-latency, high coverage, high reliability, and economically improved quality of services, categorized into three categories. Its extreme mobile broadband as a Non Standalone (NSA) architecture offers high-speed internet connectivity, greater bandwidth, UltraHD streaming videos, virtual reality and augmented reality media, between the most outstanding. 5G's machine communication capabilities are designed to be long-range, highly efficient, and cost-effective, consuming less power than previous generations (Dangi et al., 2021, p. 1). 5G has the potential to support the creation of smart cities, agriculture and transport, and the automation of digital industrial ecosystems (KPMG, 2019, p. 3). The Annexe 1 summarises the more important characteristics of the mobile technology. Worldwide, the availability of 5G could add approximately 1.3 trillion U.S. dollars to global GDP by 2030 (*Statista*, 7 September 2023). Analysys Mason estimated the total 'open innovation platform' 5G networks in Europe c.EUR210 billion in benefits excluding 5G enhanced Mobile Broadband (eMBB) consumer benefit at a cost of c.EUR46 billion (which equates to a cost–benefit ratio (CBR) of 4.5 benefit to cost). The smart production (mining; smart factories; ports and airports) and smart rural clusters (agriculture and fixed wireless access -FWA) have the largest net benefit (i.e. benefit minus cost), of c.EUR70 billion and c.EUR55 billion respectively. However, their CBRs are lower than those of the smart urban - construction - the largest cost and benefits component-; urban hotspots; stadiums- and smart automotive and smart public services clusters - healthcare and hospitals; municipal buildings; education and tourism- (Daly, Nickerson and Stewart, 2020, p. 9).

2.2 The Way to 5G

The way to 5G entailed several phases of preparedness, actions, involvement by institutions and standardisation.

As for preparedness, the following are the 5G date milestones since 2014, gathered from an institutional source (European 5G Annual Journal 2016, pp. 14-15).

2014-2015 "Exploratory phase to understand detailed requirements on 5G future systems and identify most promising functional architectures and technology options which will meet the requirements. These activities will build on previous research work in industry and research framework programmes as well as global activities in other regions and standard bodies".

2015-2017 "Detailed system R&D for all access means, backbone and core networks (including SDN, NFV, cloud systems, undedicated programmable hardware…) by taking into account economic conditions for future deployment".

2016-2018 "Detailed system optimisation by taking into account all identified requirements and constraints".

"Identification and analysis of frequency bands envisaged for all 5G communications and final system definition and optimisation by means of simulations, validation of concepts and early trials. Contributions to initial global standardisation activities e.g. in 3GPP".

"Preparation of WRC 19. Support of regulatory bodies for the allocation of newly identified frequency bands for the deployment of new systems. New frequency bands should be available around 2020".

2017-2018 "Investigation, prototypes, technology demos and pilots of network management and operation, cloud-based distributed computing and big data for network operation. Extension of pilots and trial to non ICT stakeholders to evaluate the technical solutions and the impact in the real economy. Detailed standardisation process based on validated system concepts by means of simulations and close to real world trials".

2018-2020 "Demonstrations, trials and scalability testing of different complexity depending on standard readiness and component availability".

2020 "New frequency bands available for trial network deployment and initial commercial deployment of new systems. Commercial systems deployment under real world conditions with selected customers to prepare economic exploitation on global basis".

"Enhanced mobile broadband (eMBB), with higher speed and lower latency than existing technologies, was the core consumer provision for early 5G networks, with real-world performance of up to 1 Gbps with less than 10 ms round-trip latency (Dewar, Calum et al., 2017, p. 7). In 2017, the 3rd Generation Partnership Project favoured that some operators worldwide to bring forward their 5G commercial launch plans. The specifications for non-standalone 5G new radio (NSA 5G NR) were officially approved at the end of this year as part of a wider plan to standardise the 5G system for both non-standalone and standalone (SA) (i.e. a network that uses a 5G core network without dependency on 4G LTE) models by mid-2018. The initial set of non-standalone 5G new radio (NSA 5G NR) specifications, approved at the end of this year, enabled manufacturers to advance their tests, build and design components that implemented the 5G new radio specifications, while awaiting final standardisation" (GSMA, 2018, pp. 12-13).

As for actions, involvement by institutions and standardization, radio spectrum is a key issue. It is a scarce natural resource, which must be conferred to operators of the service through different pathways. Between them, auctions can determine the most efficient and effective mobile providers, while ensuring compliance with their public service obligations laid down by the regulator. Well-designed spectrum auctions are economically efficient if they allocate parts of the radio spectrum to the best societal use. Several challenges hinder spectrum auctions, such as the complementary nature of spectrum lots, incentives for firms to engage in strategic bidding, effects on downstream markets, and uncertainty. Competition considerations play an important role when using spectrum auctions to award strategic assets in oligopolistic markets (Myers, 2023, pp. 3-4, 118 and 178).

Having established the technological potential of 5G, the next logical step is to understand the economic implications of its deployment. As we move forward, it's crucial to examine not just the technologies themselves but the investment and regulatory challenges that impact the roll-out process. In other words, the aim is to explain how technological advancements impact cost structures or investment priorities.

2.3 Investment, Expenditure, Costs

A number of considerations have to be made in relation to investment. New infrastructures for 1G and 2G required large investments. The 2.5G intergenerational upgrade was introduced through the deployment of an overlay packet network in the form of General packet radio service (GPRS. 3G enabled to separate in time the investment in new radio access and new core equipment, according a sequence of new radio (wideband CDMA), which became interoperable with the existing 2G circuit -switched and 2.5G packet-switched core. In 3.5G, packet capabilities moved to High-Speed *Packet* Access. In 4G, the circuit core was abandoned and the packet core was upgraded while a new modulation technique was applied in radio access (OFDMA), which required upgrades to base stations and terminals.

5G challenges the level of investment required. The specialised agencies allocated a substantial share of the investment in that standard to the private sector. Nevertheless, they linked the successful deployment of the new technology to joint action by telecoms operators, policymakers and the entire digital ecosystem. Governments play a crucial role in establishing a robust industrial policy to support digital communications and ensuring a regulatory framework that encourages investment (European Telecommunications Network Operators' Association, 2020, p. 17). There is also considerable uncertainty about the business case for mobile operators to invest in supporting innovative services (Frontier Economics Ltd., 2021, pp. 31-32).

Beginning by the cost considerations, the increased complexity and coverage density of 5G base stations to meet the planned capacity has led to estimates of a much higher cost (perhaps triple) of 5G deployment than previous standards. The European Commission estimated the cost of achieving its 2025 connectivity targets, which include 5G coverage in all urban areas, at €500 billion (Blackman and Forge, 2019, p. 6).

Second, significant evidence reveals different cost structures between the mobile network operator and those of fixed network operators due to a number of factors. The main single difference lies in the treatment of the access network (base stations and associated equipment). In a fixed network (predominantly the copper loops) it is entirely driven by the number of subscribers, as each subscriber has a dedicated line. The size and costs of this line, and the customer access network as a whole, are therefore invariant to the amount of traffic throughput and are causally related to the number of subscribers and independent of traffic volume. Subscription revenues allow appropriately recover such costs.

Conversely, the mobile networks don't have an access network dedicated to individual subscribers and are sized to support the traffic arising from outgoing and incoming calls. Therefore, an increase in traffic does require further investment in the access network, so that the costs of the access network are causally related to the volume of traffic and are appropriately recovered from traffic services (KPMG, 2019, p. 3).

The costly deployment of 5G networks may lead to alternative infrastructure ownership models and policies which could reduce the costs in terms of spectrum policy, network sharing, consolidation, equipment costs and other rollout barriers. The release of additional spectrum for mobile use could support increased traffic demand and the development of advanced use cases (Small Cell Forum, 2017).

Sharing infrastructure and equipment reduces overall costs by eliminating the duplication of fixed costs and make ventures financially viable.

5G offers even stronger cost savings potential for network sharing because, as it avoids the cost of network consolidation. Beyond cost, it could solve many practical roadblocks in urban areas, such as the potential for urban disruption and visual pollution from the installation of excessive equipment and fiber (Grijpink et al., 2018, pp. 1-5; Grijpink et al., 2018a) (Note 3). Several administrations promoted network sharing agreements between operators with a reduction of infrastructure costs that have been estimated in 16%-35% on both capital expenditure (capex) and operating expenses (opex) for passive agreements and even more active agreements. These cost savings could help accelerate the deployment of 5G technology (Note 4). Furthermore, consolidation of mobile networks would remove the need to duplicate mobile infrastructure, thereby reducing the fixed costs of roll-out between the two merging operators. Mobile operators which worry about the lack of choice of equipment vendors could reduce equipment cost increases through OpenRAN. It is an option to enable interoperability between different hardware and software vendors, which increases choice, competition and innovation. In terms of other barriers to deployment, policy decisions should enable the development of rights and the Government's Barriers Task Force has significantly improved the ability to roll out (Frontier Economics Ltd., 2021, pp. 31-32).

An evolutionary approach to infrastructure investment was undertaken in the first commercial rollout wave of 5G (Grijpink et al. p. 2), closer to 4G+, both being non-standalone networks (KPMG, 2019, p. 13; O'Donnell, 2019; Gabriel, Chen and Goldman, 2020, p. 6) (Note 5). 4G infrastructures were the base in the initial 5G services in several countries in Europe (Daly, Nickerson and Stewart, 2020, p. 4).

From the supply side, as concerns network infrastructure, the long lifetime and high cost of equipment has been driving network infrastructure manufacturers and others to develop upgradeable software versions of their mobile tower equipment for several years now. In particular, a major effort has been made to produce equipment that can be easily upgraded from 4G Advanced LTE to 5G NSA. Software-only upgrades are possible because of much of the sub-6 frequencies eligible for 5G are also currently used for 4G. As a result, it is possible to dispense with new antennas and other radio access network, or RAN, equipment to support these frequencies when they want to switch their networks to 5G (O'Donnell, 2019) (Note 6).

Think of 5G's network slicing as creating different lanes on a motorway. Some lanes are designed for fast cars (high data traffic), while others are for trucks (devices requiring less data). This ensures smoother traffic flow and greater efficiency for all vehicles.

Both large and small and medium-sized enterprises (SMEs) in 2018 mobilised private investments that sum up to an amount 10.12 times the public EC investment in the 5G PPP in the same period. All the types of stakeholders/beneficiaries invested in 2018 a total amount of money that is 7.24 times the public investment in the same period (European 5G Annual Journal 2020, p. 101).

Worldwide telecommunication capex sharp rose by mid-2022 reaching its highest in more than ten years, above the LTE peak of 2015. MTN Consulting calculated that capex came to $329.5 billion over the preceding twelve months. Among several factors, a large part of the explanation is that communications service providers (CSPs) were simply making up for time lost during the Covid-19 lockdowns, which depressed network expenditure and deployment (Taaffe, 2022).

2.4 R&D

Let us not forget that we are following a multifactorial scheme. Next to infrastructure, R&D accounts for a substantial component of total expenditure. The state-owned national monopolies financed the next generation R&D while the introduction of competition shifted the emphasis to pre-competitive EU R&D programmes involving hardware manufacturers, carriers and academic research institutes. Throughout the 3G phase, operators put network-related R&D in the hands of equipment manufacturers and refocused their R&D activities on service provision. 5G-oriented research within the EU-funded Frame Programme 7 (FP7) and Horizon 2020 programmes aligns with this trend, in terms of timing, content and industry participation. Strategic R&D collaboration agreements on 5G have been reached between the EU and Japan, Korea, China and Brazil (Lemstra, Cave and Bourreau, 2017, pp. 22-23).

Research and development remains a strategic priority for companies, even during turbulent times, which were used to extend their competitive advantage. According a survey conducted by McKinsey (2009), approximately 40% of the respondents stated that their companies were actively seeking to reduce R&D costs and trimming the number of R&D projects. 34% of the executives surveyed revealed R&D budgets for 2009 lower than those for 2008. Moreover, a significant majority of respondents indicated that their companies were adopting a new approach to R&D. Specifically, many were pursuing shorter-term, lower-risk projects or making minor modifications to existing products. Additionally, some findings suggested that many companies might be neglecting long-term innovation opportunities. The companies that derived the greatest benefits from innovation seemed to be taking a distinct approach, namely the increasing of their R&D budgets and activities, and the shift towards longer-term, higher-risk projects. Additionally, they were almost twice as likely to report that they viewed the downturn as an opportunity to upgrade their R&D**.**

As ZK Research points out, telecommunications companies have historically raced not to innovate, but to offer cheaper prices than their competitors. That's led to cutting R&D spending to slash expenses more broadly.

The high amount of expenses in R&D required in 5G came from several sources, mainly from infrastructure vendors and Huawei at the head, followed by Samsung (Figure 1 and Annexe 2).

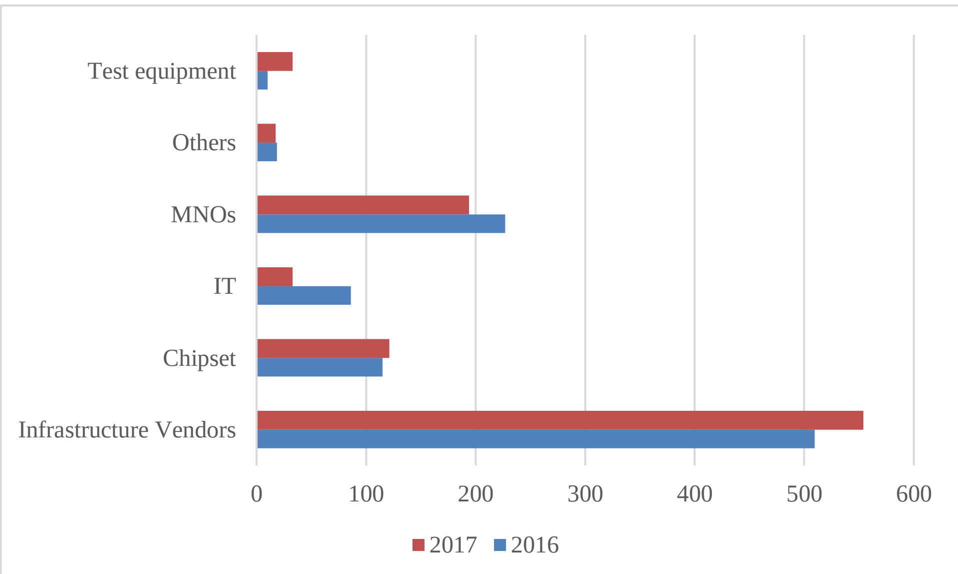


Figure 1. 5G Private R&D expenses (as 2% of total R&D), 2016-2017

Source: Elaborated from *The European 5G Annual Journal*, 2017, p. 65.

3. Deployment 5G Around the World

The mobile industry progressed with 5G successful trials around the globe and the approval of the non-standalone 5G new radio specifications in December 2017. Early 5G commercial launches were expected over the following three years in the United States and major markets across Asia-Pacific and Europe (GSMA, 2018, p. 4). The most advanced countries in their plans for 5G were the USA, China, Japan, the Republic of Korea, Singapore and Taiwan (Blackman and Forge, 2019, pp. 13-15).

The USA moved towards 5G deployment through a series of commercial manoeuvres, some of which were more about rebranding existing LTE than offering new networks. One example of this was the reuse of LTE spectrum in the UHF ranges (300 MHz to 3 GHz), probably justified by its geography of large rural areas and high-density urban centres located rather on the coasts. A major challenge is the local administrative barriers to small cell deployment, the need for which entails long delays and high costs. The prevalence of local regulations over the FCC led to a major divide between local and central government over the authorisation of deployment and the fees for it (Blackman and Forge, 2019, pp. 13-15).

A slow rollout was expected in China, perhaps beginning later in 2019 (Blackman and Forge, 2019, pp. 15-19). Regarding critical technologies for 5G, Korea and Taiwan hold leading positions in the field of integrated circuit (IC) and their governments urged them to expand. In Korea, Samsung and SK Hynix, the second largest player, aimed to leave the old fashion Chinese IC plants out of the new 5G market by investing quickly and on a massive scale. Therefore, Korea's interests were served by a fast rollout of 5G networks to perfect its 5G chipsets in the field (Blackman and Forge, 2019, pp. 22-25). The three South Korean mobile operators, KT, LG U+ and SK Telecom, led the global launch of mobile 5G services. They all started their services on the same day in April 2019, just hours before Verizon in the USA (Sale 2020) (Note 7); Table 1). In 2021, 4G dominated the total connections (excluding licensed cellular IoT) with 75%, well above the 14%, 7% and 4% of 3G, 2G and 5G, respectively (GSM Association, 2022, pp. 3 and 11).

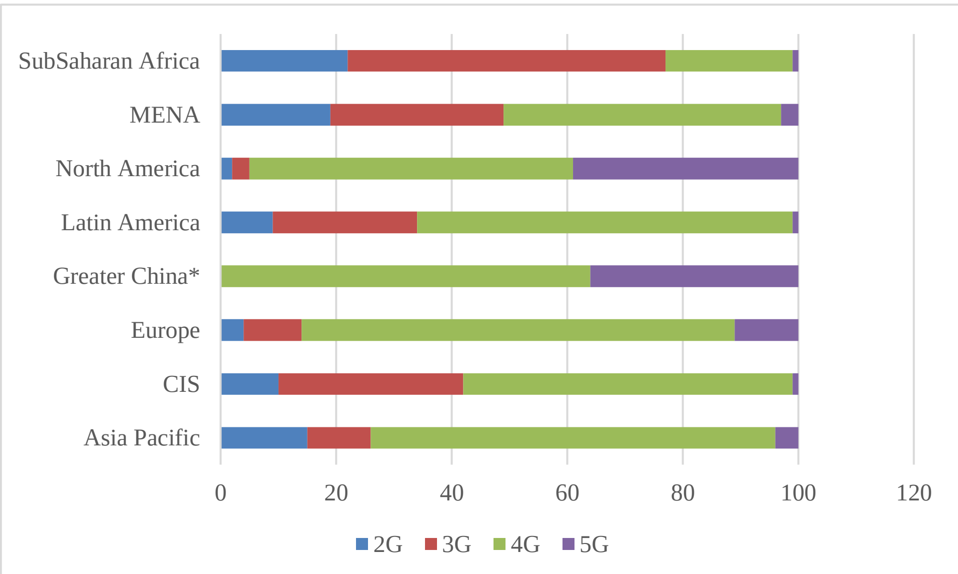


Figure 2. Technologies of mobile communication in 2022 (%)

Source: Elaborated from GSMA (2023), pp. 8-9.

Still in 2023 the 4G-LTE deployments multiplied by a factor of 2.43 the 5G deployments (5GAmericas, 2023). 5G will overtake 4G in 2029 to become the dominant mobile technology by the end of this decade (GSMA, 2023, p. 13).

Table 1. Adoption and deployment of 5G in the world

Country	Market	Country to deploy 5G services	Government initiatives to deploy 5G networks
South Korea	3 main MNOs: SK Telecom (the largest); KT; LG Uplus	early mover; second country to deploy	to encourage network sharing between MNOs; tax benefits and security maintenance services

USA	3 nationwide MNOs: Verizon, AT&T; T-Mobile	first country (Verizon)	5G FAST Plan (pushing more spectrum; updating infrastructure policy; modernising regulations
China	3 state MNOs: China Telecom, China Unicom; China Mobile	launch in October 2019	state-backed initiatives: rebates and subsidies; local schemes
Europe	3 large MNOs and a fourth, smaller MNO	launch in summer 2019	Action Plan (2016): promoting early 5G deployment; encouraging industry-led innovation; €700 million for R&D+i over seven years; member states schemes

MNO: mobile network operators.

Source: Elaborated from KPMG, 2019, pp. 16-19 and 21-24.

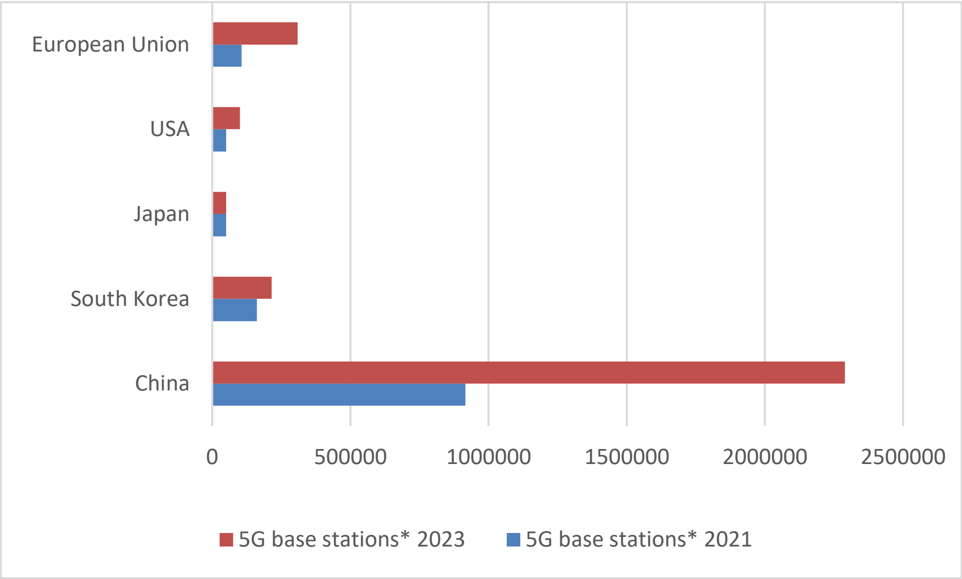


Figure 3. International 5G developments, 2021-2023

Source: Elaborated from *5G Quarterly Reports*, 2021-2023.

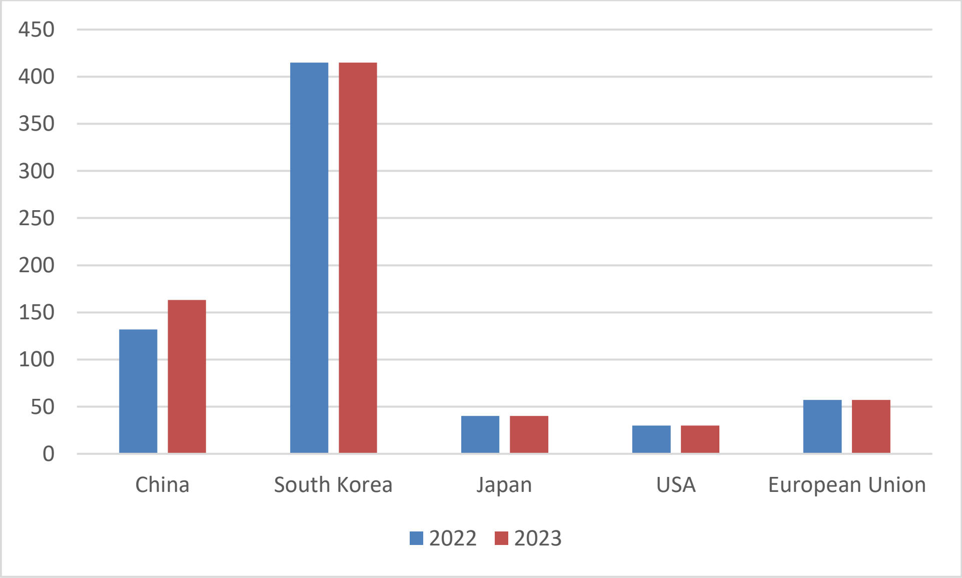


Figure 4. International 5G developments in 2022-2023. 5G base stations/100.000 inh.

Source: Elaborated from *5G Quarterly Reports*, 2021-2023.

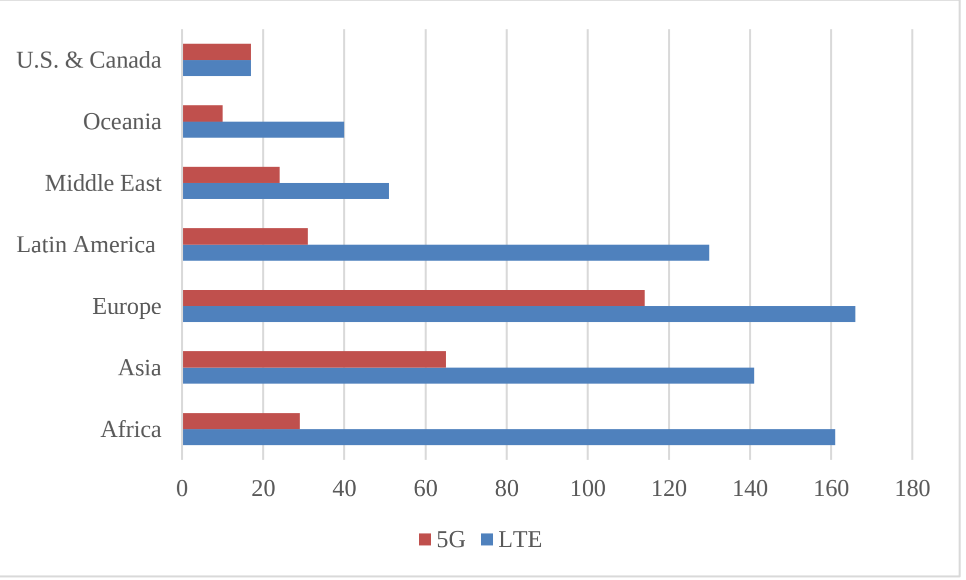


Figure 5. International 5G versus 4G developments

Source: Elaborated from *TeleGeography*, 17 October 2023.

Mobile connections excluding cellular IoT in 2025 provides a view of the 5G adoption by major countries/regions. China leads the expectations with 396 million of 5G connections, followed by Europe (21/), US (191) and Japan (87). This panorama changes when the 5G share of total mobile connections given that of a total of 1.224 million of connections US leads with 49%, followed by Japan (45%), Europe (31%) and China (25%) (GSMA, 2018, p. 32).

4. Deployment 5G in Europe

The European Commission set a milestone in September 2016 with the 5G Action Plan. Through its strategic initiative, it aimed to extend fifth-generation mobile services to all Member States within four years and to ensure seamless 5G coverage in preferred areas within five years. Very high capacity networks generating around €225 billion in annual revenues for mobile operators worldwide will be a key asset for Europe to compete in the global market. The Action Plan set out a clear roadmap for public and private investment in 5G infrastructure in the EU with six actions. They comprised, firstly, a coordinated network roll-out, starting by 2018 and moving towards full commercial deployment by the end of 2020 at the latest. For 2019 there would be interim spectrum bands, to be followed by new ones. The third action prioritised early deployment in major urban areas and along major transport routes. An important issue was the promotion of pan-European multi-stakeholder trials as a catalyst to turn technological innovation into complete business solutions. In addition, an industry-led venture fund was advocated to support 5G-based innovation. Finally, it was intended to bring together key stakeholders to work on promoting global standards (European Commission 5G Action plan. https://digital-strategy.ec.europa.eu/en/policies/5g-action-plan).

5G presented a strategic for Europe for a number of reasons. 5G is pivotal to a major global technological, industrial and innovation transition and will enable many business applications with significant potential for economic growth and innovation in a wide range of sectors. The development of equipment and applications 5G technologies is a key vector of innovation and a driver of Europe's strategic digital autonomy. It is also a means to support Europe's autonomy and role in the sector to maintain a strong position in the global market. It was expected to improve the efficiency and resilience of European supply chains and industrial ecosystems. New communication possibilities could emerge to support industrial processes, potentially increasing efficiency and opening up new ways of doing business, as well as enabling SMEs to participate more actively in the communication ecosystem (Lefebvre, Gigler and Borg, pp. 5-7).

For the deployment of 5G, mobile network operators require access to sufficient spectrum to ensure optimal performance and coverage, particularly in the 700 MHz, 3.4-3.8 GHz, and 26 GHz frequency bands. European regulators aimed to guarantee that at least three mobile network operators had access to spectrum in the key 3.4-3.8 GHz band and to promote sufficient competition when designing spectrum auctions. The regulators increasingly prioritised simplicity, fairness, and transparency in the auction design process with simpler auction formats as simple clock formats, Simultaneous Multi-Round Auction (SMRA) & clock-SMRA hybrid. Those are all first-price formats in which bidders generally place only up to one bid per lot category per round. On the contrary, three countries acted on an exclusive track: Ireland with a combinatorial clock auction (CCA) (Note 8)in 2020 while Norway (2020) and Denmark (2021) with the *Combinatorial* Multiple Round Ascending (CMRA) format (Kasberger and Teytelboym, 2022).

Between 2017 and 2021, most European regulators allocated spectrum in some of the 5G frequency bands. The 3.4-3.8 GHz band was assigned in most European countries, while the 26 GHz band was only assigned in a few (Marquardt, Gallagher and Abate, 2021, pp. 1-5). By the end of March 2022, all of the 27 Member States but two (Estonia and Poland) had assigned spectrum in the 5G pioneer bands (700 MHz; 3.6 GHz and 26 GHz band). Six countries -Germany, Croatia, Denmark, Greece, Finland and Slovenia- assigned more than 90% of spectrum (The Digital Economy and Society Index 2022, pp. 36-37).

Table 2. Nation state 5G spectrum assignment to 2021

Nation	Consultation	700 MHz	3.4-3.6 GHz	3.6-3.8 GHz	>24 GHz	Other frequencies
Austria	2017	September 2020	March 2019 190 MHz	March 2019 200 MHz	ongoing 2021	1500, 2100, 2300MHz
Belgium		2021 400 MHz	2021 400 MHz			1.5, 31.8-33.4, 40.5-43.5 GHz
Bulgaria	2017	-	April 2021	April 2021	ongoing 2021	1.5GHz/2500MHz/2600 MHz
Croatia	March 2019	2021*	2021, partially 230 MHz	2021, partially 100 MHz	ongoing 2021	2.5-2.69 GHz, 1500 MHz
Cyprus	December 2018	December 2020	December 2020	December 2020	ongoing December 2020	December 2020*
Czech Republic	January 2020	November 2020	November 2020	July 2017	ongoing 2021	+ 450 MHz
Denmark	March 2019	April 2021	April 2021	April 2021		March 2019: 800/900 MHz and 2300-2400 MHz
Estonia	March 2019	Ongoing 2021	Ongoing 2021	Earmarked 2021	*	40.5-43.5 and 66-71 GHz
Finland	2016	October 2018	October 2018	June 2020	Earmarked 2021	-
France	July 2018	2015?	October 2020	October 2020	Earmarked 2021	1.5 GHz, 2.6 GHz TDD
Germany		2015	June 2019	ongoing 2021	26 GHz on demand	2000 MHz
Greece	October 2018	December 2020	December 2020	December 2020	26 GHz December 2020	1500 SDL/2100/2300 MHz
Hungary	November 2017	March 2020 5 lots of 2x5 MHz	2016 80 MHz	March 2020 310MHz		2.1 GHz/2.6 GHz (no bids)
Ireland	March 2019** revised May 2020	Ongoing 2021	May 2017	May 2017	June 2018 P2P links: 24.745 – 25.277 GHz paired with 25.753 GHz – 26.285 GHz	2.1/2.3/2.6 GHz
Italy	Dec. 2017, Feb. 2018	September 2018 60 MHz		September 2018 200 MHz	September 2018 1,000 MHz	-
Latvia	2022	2022 Ongoing	November 2017 (September 2018: unsold spectrum)	November 2017, (September 2018: unsold spectrum)		2021: 1500 MHz

Lithuania	2018	2021 Ongoing	2021 Ongoing	2021 Ongoing	-	3.8-4.2 GHz
Luxembourg	November 2018	July 2020	July 2020	2021 Ongoing	earmarked	1.5 GHz, 900/1800 MHz
Malta	February 2021	April 2021 On demand	April 2021 On demand	August 2021	April 2021 On demand	800 MHz, 1.5 GHz, 2.6 GHz
Holland	Dec 2018	July 2020	Ongoing 2021	*	2021 Ongoing	2100/1500 MHz
Poland	2018	First half 2021	Q1 2021	Q1 2021	2021 Ongoing	-
Portugal	2018	Q1 2021	Q1 2021	2023?	Earmarked	450 MHz/900 MHz/1500 MHz/1800 MHz/2100 MHz/2.6 GHz
Romania	2018	Q2 2021	Q2 2021	Ongoing	upper parts of 26 GHz, >1000 MHz	-
Slovakia	2018	November 2020	2015 Ongoing	2017 Ongoing	Earmarked	April 2021: 900/1800 November 2020 1500 MHz
Slovenia	2017; May 2019	April 2021	April 2021	April 2021	April 2021	April 2021: 1400 MHz, 2.1/2.3 GHz
Spain	2017	Q1 2021	2016	2018	Earmarked	-
Sweden		December 2018	January 2021 (320 MHz)	January 2021 (320 MHz)	Earmarked	Ongoing 1.5/2.6 GHz, 2.3 GHz auctionned
UK	March 2017, Updated 2018	Early 2021	April 2018	Early 2021*	On demand	1.5/2.6 GHz
Norway	Feb 2019					

* Allocation procedure scheduled; ** National roadmap

Source: Elaborated from 5G Observatory, 2021.

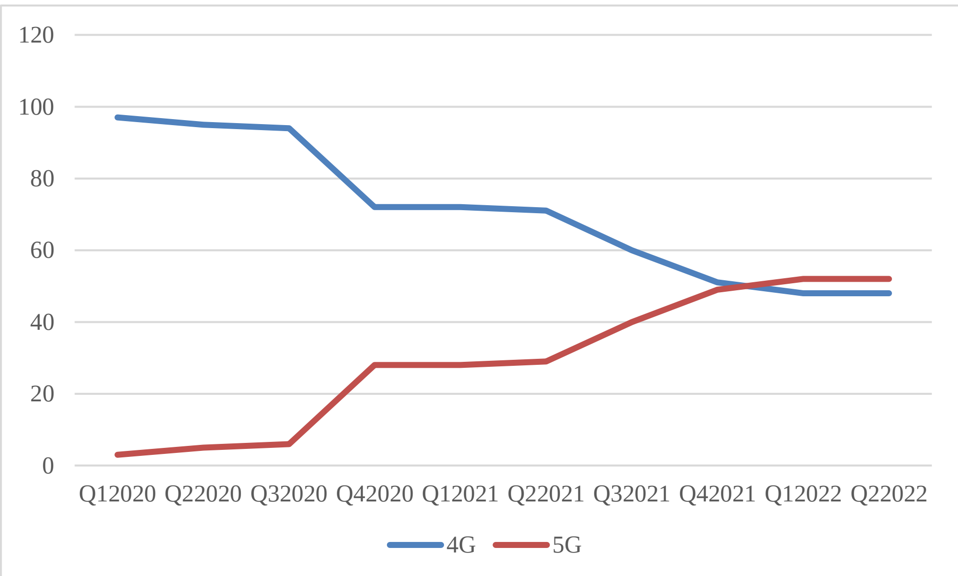


Figure 6. European smartphone shipments by network technology, 2020-2022 (%)

Source: Elaborated from Canalys, 21 October 2022.

According to estimates by specialised agencies (GSM Association, 2022), 5G would overtake 3G in Europe by 2023 and narrow the gap with 4G, which would remain dominant. In the first quarter of 2022, 5G-based smartphone shipments overtook 4G-based smartphones in Europe (Figure 6) and more than half of the smartphones shipped in Europe in the first half of 2022 were 5G-enabled, and most of these devices were mid- to high-end models.

In the early rollout for 5G, the EU performed quite well, for reasons of its economic structure. First, Europe has two of the major network equipment producers in Nokia and Ericsson, which hold about half of the global telecoms equipment market as well as some core patents. Some important semiconductor suppliers (e.g. ARM, NXP) are located in the EU. Also, the EU hosts the key institution for 5G international standards, ETSI/3GPP, which means it houses the centre of intelligence on the technologies, standards and patents that underpin them. There are also four practical factors associated with 5G deployment. As a key factor it was the ease with which a large number of small cells can be deployed in densifying the network. The three remaining factors are the following: significant competitive advantage coming from a government with political power down to local authority level; the scale and who is the driving force behind the 5G marketing activity and, finally, the critical size of the home market to support the first versions of local 5G products and the national market testing to improve them (Blackman and Forge. 2019, pp. 22-25). The position of the political forces and the population, sometimes influenced by conspiracy theories that hinder the positive influence of telecommunications, in favour or against is of vital importance (Note 9).

Austria pioneered the 5G in Europe when *T-Mobile Austria* rolled out 5G network in the *non-standalone* (NSA) configuration, which built the basic blocks of 5G onto existing 4G networks (Curwen and Whalley, 2021, p. 22) (Note 10).

In 2019, three operators in two countries – T-Mobile in Austria; Vodafone and Eir in Ireland- launched commercial 5G services in the configuration Non Standalone. A great number of launches occurred in 2020 in numerous countries, both big powers (France, Germany, UK) (Note 11) and small ones (Slovakia, Slovenia, Estonia, etc.). In the following year there were 29 new launches in Europe. In January 2022, all 27 EU Member States had commercial 5G available (https://5gobservatory.eu/overview-5g-commercial-launches/).

In mid-2022, Belgium completed the 5G spectrum auction in the 700 MHz, 1800 MHz, 2.1 GHz and 3.6 GHz bands with a total of EUR 1.2 billion raised. The three incumbent mobile operators - Orange Belgium, Proximus and Telenet - acquired 100 MHz of mid-band spectrum. New entrant Citymesh, currently focused on private networks, gained 50 MHz in the 3.6 GHz band and 2 x 5 MHz in the 700 MHz band (European 5G Observatory, 29 June 2022).

In Romania, three operators - Vodafone, Digi and Orange - launched 5G services in 2019, well ahead of Telekom Romania, a subsidiary of Deutsche Telekom Group and the country's fourth largest national operator. The operator rolled out its 5G network in eleven cities, with the country's capital, Bucharest, leading the way (European 5G Observatory, June 21st, 2023).

In Lithuania Tele2 launched 5G at the end of September 2022 once spectrum was acquired. Tele2 activated 5G base stations in the capital city of Vilnius using spectrum licences it acquired in the 700 MHz and 3.6 GHz bands. The operator planned to expand its service to other major cities. Tele2 used Nokia 5G equipment for both the core of their network and the Radio Access Network.

Table 3. Commercial 5G launches

Country	2019	2020	2021	2022	2023
Austria	T-Mobile	A1 Telekom		Three Austria	Three Austria
Belgium		Proximus	Telenet	Orange Belgium	
Bulgaria		Vivacom A1	Telenor	Vivacom	
Croatia			Hrvatski Telekom		
Croatia				Telemach Croatia	
Cyprus			Cytamobile-Vodafone		
Czechia		Vodafone O2 (Telefónica) T-Mobile			
Denmark		TDC Telenor Telia Denmark Hi3G Access		Telenor	Hi3G Access

Estonia		Telia		Elisa Estonia	
Finland				Elisa Oyj	
France		Free Bouygues Telecom SFR		Bouygues Telecom SFR	
Germany				Deutsche Telekom Vodafone 1&1 Telefonica Deutschland (O2)	Deutsche Telekom Telekom Deutschland Vodafone Germany Telefonica Deutschland
Greece		Wind Hellas Cosmote	Vodafone Greece	Cosmote	
Hungary		Magyar Telekom Vodafone	Telenor		
Ireland	Vodafone Eir	Three Ireland			
Italy			Vodafone Telecom Italia (TIM) Fastweb Windtre	Windtre TIM	
Latvia			LMT Tele2		
Lithuania			Telia	Telia	Telia Lietuva Bite Lithuania
Luxembourg		Orange Tango Post			
Malta			Melita Epic		
Netherlands		VodafoneZiggo T-Mobile KPN			
Poland		Orange Poland Play T-Mobile			
Portugal			NOS	MEO	
Romania			Vodafone Digi Orange		
Slovakia		Slovak Telekom	Orange O2	O2	
Slovenia		Telekom Slovenije			A1 Slovenia
Spain		Orange	Telefonica MasMovil	Orange Spain Vodafone Spain Telefónica	Vodafone Spain Orange España
Sweden		Tele2 Telia Sweden Tre	Telenor	Tre Sweden	

Source: Elaborated from https://5gobservatory.eu/overview-5g-commercial-launches/

In 2021, 4G coverage was almost universal, reaching 99.8% in populated areas in Europe and 99.6% in rural areas. 5G commercial services were launched in all but two Member States (Latvia and Portugal) by mid-2021. Initially, Finland ranked first in population coverage (over 50%) whereas most countries were at coverage of 15–40% (Daly, Nickerson and Stewart, 2020, p. 4). 5G coverage grew substantially from 14% in 2020 to 66% of populated areas. Broadband coverage of rural areas35 remained challenging, as 8.5% of households were not covered by any fixed network, and 32.5% was not served by any NGA technology. On fixed technologies, there was a marked increase in the rural coverage of FTTP (from 26% in 2010 to 34% in 2021) (The Digital Economy and Society Index 2022, pp. 30-31).

In 2023, the 5G coverages had increased substantially, as Figure 7 displays. Three small countries ranked first (Cyprus, Malta and the Netherlands), narrowly followed by five others of varying size and importance. This was followed by large powers such as France and medium-sized ones such as Spain. Two countries (Romania and, surprisingly, Sweden), below the EU27 average, closed the list.

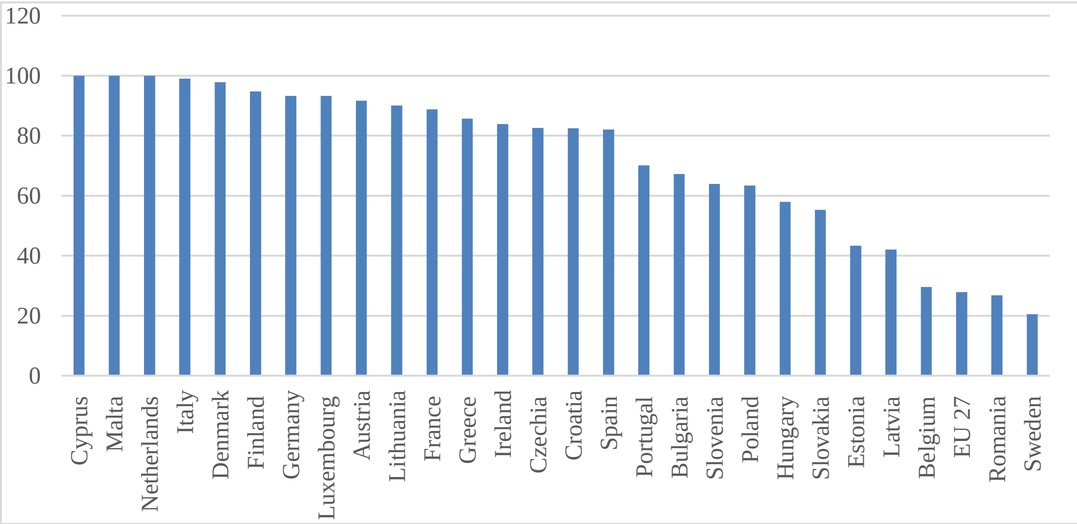


Figure 7. 5G Population coverage in Europe27 (%), March 2023

Source: Elaborated from 5G Observatory Biannual Report, April 2023

5. Europe's Backwardness: A First Approach

After all this has been said, a key point remains to be clarified: why Europe lags all global peers in coverage, speed and usage of 5G (Wood and Sherrington, 2024, pp. 4-5).

The EU, with pre-eminent manufacturers of handsets headed by Nokia, PCs and semiconductors, dominated the first phases of the mobile phone industry. 2G GSM enjoyed an extraordinarily rapid diffusion in Europe, notably as a result of the adoption of a unified standard from the outset, which gave a significant competitive advantage to European operators. Nevertheless, the region fell behind in 4G technology (Ortega, 2021; Fuentelsaz, Maícas and Polo, 2008, pp. 433-449). Some observers noted that the region was about two years behind the United States in 4G network investment and adoption (IDATE/Ericsson, 2015). Mid 2013, three out of every four inhabitants of the EU can't access 4G/LTE mobile connections at hometowns while in the United States over 90% of people have 4G access, and virtually no rural area has 4G (European Commission 2013). This correlates with the long-term trend of Europe's GDP gap relative to the United States and Japan, which Crafts (2011, p. 1) refers to as lacklustre growth in Western Europe from the mid-1990s until the 2008 financial crisis versus accelerating productivity growth in the United States.

What are the reason(s) why a pioneer has become a second-class player? In 2021, the 5G penetration rate among European citizens had doubled from 24% in 2020. Nevertheless, the 5G development and roll-out in Europe behind that of the United States and Asia. As of 2023, Europe's 5G penetration rate was 23%, compared to 56.9% in China and 32.6% in the U.S. These numbers highlight a significant gap in deployment and adoption.

In 2022, South Korea reported 98% 5G coverage, while Europe lagged behind with only 80% coverage in some countries. This gap is reflected not only in infrastructure deployment but also in speed and usage.

In 2023, 23% of mobile connections in the European Union were 5G, 32.6 points under the US figure, 16 under Japan, 34 under South Korea or 56.9% under China (Analysys Mason, January 2024; ETNO The State of Digital Communications, 23 October 2024. https://etno.eu/library/reports/117-sta-te-of-digital-2024.htm). In 2023, 5G coverage in Europe reached 80% of the population, an increase of seven percentage points from the previous year. However, Europe still lagged behind all its global counterparts, with South Korea (98%), the United States (98%), Japan (94%), and China (89%) leading the way. The European median mobile downlink speed was 33 Mbit/s, 57 and 107.5 lower than that in the USA, South Korea and China, respectively. Standalone 5G coverage of only 40%, 51% and 5% percentage points lower than in North America and Asia-Pacific respectively, puts Europe behind its global competitors in 5G deployment (Euronews, 28 January 2025).

Additionally, European mobile usage is comparatively low. In 2022, the average monthly usage in Europe (14.2GB) was 3.3, 2.0, and 1.4 GB lower than in South Korea, Japan and the USA. Europe has been slow to adopt two key technologies: 5G SA and 11 had RAN and edge-cloud. Of the 114 operational 5G networks in Europe, only 10 included 5G SA and 11 had RAN technology developments. Europe has only four edge-cloud commercialised offers, which remain at the heart of network virtualisation, compared to Asia's 17 and North America's 9 (European Telecommunications Network Operators' Association, 2024, p. 5).

Some authors (White, 2022) attributed the situation to a number of factors, including delayed spectrum auctions, a global shortage of chips, and the existence of a digital divide. The COVID-19 pandemic prevented auctions across Europe from going ahead (European 5G Observatory, 3 April 2020). Europe demonstrated a lack of consistency in its approach to the auctioning of spectrum bands for 5G, with Finland auctioning all the necessary bands, while Poland, Portugal and Belgium were yet to complete any auctions. In August 2020, the U.K. regulator Ofcom postponed the auction of spectrum until January 2021 and then until March 2021 (Total Telecom, 25 January 2021; S&P Global, 25 January 2021; https://www.ofcom.org.uk/spectrum/spectrum-management/spectrum-awards/700-mhz-and-3.6-3.8-ghz-auction). The financial implications of these auctions could also impede the rapid deployment of 5G via high starting prices or inflated prices due to a limited amount of available spectrum. Approximately one-third of all semiconductors produced are destined for use in communications equipment, including routers and base stations (Semiconductor Industry Association). A shortage of these devices could result in delays in procurements by CSPs, thereby slowing down the deployment and expansion of 5G networks (White, 2022, p. 5).

Is it fair? The complexity of the issue calls for a more detailed analysis. To begin with, the European telecommunications sector as a whole continues to underperform global peers in terms of revenue and investment and is losing size and global competitiveness. In 2022, the average revenue per user (ARPU) for mobile services in Europe was EUR15.0, EUR27.5, EUR11.5, and EUR10.9 less than in the USA, South Korea, and Japan, respectively. The fixed broadband ARPU in Europe was EUR35.8 less than in the USA and EUR1.6 less than in Japan, but higher than in South Korea. In terms of underperformance in revenue, the telecoms capex per capita in Europe stood at EUR109.1, EUR161.7 lower than in Japan, EUR131.8 than in the USA and EUR4.4 than in South Korea (European Telecommunications Network Operators' Association, 2024, p. 5). In 2021, ETNO forecasted €300 billion of additional telecommunications network investment by Europe to complete the rollout of 5G networks and Gigabit-capable fixed infrastructure (Telecoms, March 25, 2021). The EU now sets a minimum of €174 billion in new investment needed until 2030 to meet the Digital Decade connectivity targets. Finding the source of this investment and the optimal way to financially structure a long-term sustainable 5G ecosystem remain two of the most hotly debated topics today (EU, 2024, Brussels).

Leadership in 5G can give an opportunity to position Europe at the forefront of the global digital economy through seven policy actions. Investment concerns two of them, i. e. the increase of the amount without sacrificing price efficiency and to adequate spectrum supply and simplified, long-term licences (GSMA, 2016).

Network sharing became increasingly common since 2010. In Europe, this practice is common, and encompasses two situations with different strategic rationales: sharing a superior network between two leaders in a four-player market to polarise the market or joining forces between two attackers to improve network quality and jointly compete against the market leader. Europe outperformed other areas in cumulative number of active network sharing agreements in 2020-2017. In the latter year, 40 out of a total of 98 came from Europe (Grijpink et al., 2018a, p. 2).

In addition to central aspects such as regulation and investment, demand factors must also be taken into account. We therefore make a brief reference to users' attitudes towards 5G, while noting that there is a dearth of research on the subject, with rare exceptions (Mishra et al. 2024, pp. 1-10).

ETNO found in a study that, although by 2020 almost all Europeans had heard of 5G, only 1 in 4 Europeans claimed to know the technology well. Of this quarter, 24% were very familiar with it, especially among younger people, almost half were more or less familiar with it (49%), 23% knew it only by name and 4% were unfamiliar with it. For every negative European about 5G, there were 5.5 positive ones. The positive/negative ratio varied greatly between European countries. Younger Europeans have a more positive attitude towards 5G while older Europeans are more often neutral towards 5G. Attitude towards 5G was closely related to a good knowledge of 5G. As for advantages of 5G, higher speed and capacity were the most known 5G advantages over 4G (69 and 49%). Europeans with a better understanding of 5G were better aware that 5G enables new technologies possibilities. While Europeans considered 5G important for business and development of innovations, they were much less convinced about it becoming important for their personal day to day lives. More modest values presented the superiority of 5G over 4G in terms of stability, vertical application capability, including connection to vehicles and autonomous driving, ability to support virtual reality and augmented reality, ability to use other devices from mobile health remotely (ETNO 2020, pp. 9-12; 14-15; 27-28).

It appears highly likely that one of the factors of Europe's backwardness lies precisely in one of those that some studies (White, 2022) do not consider, namely the investment problem.

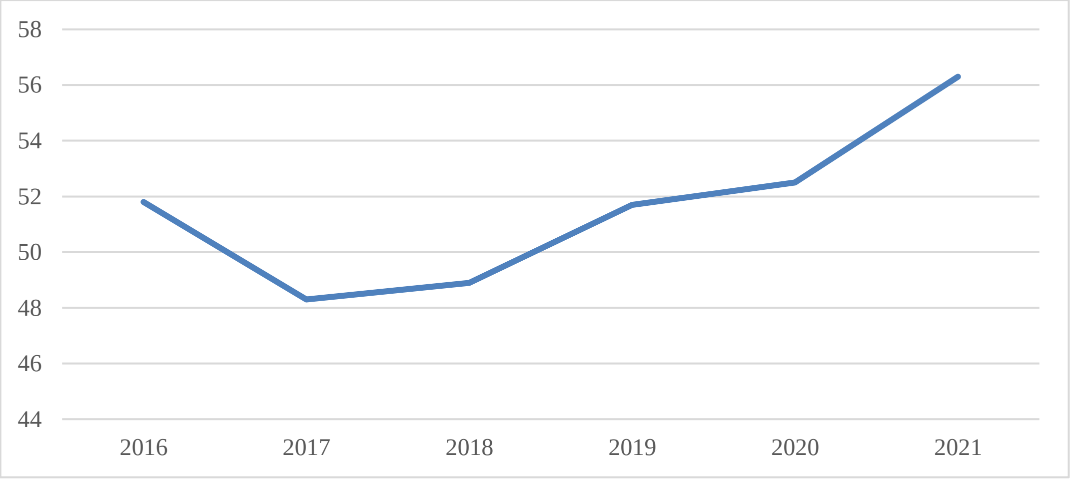


Figure 7. Total capex in Europe, 2016–2021 (€ billion)

Source: Elaborated from ETNO, State of Digital Communications 2023 (Analysys Mason, 2022), p. 29

During 2014-2020, the EU fostered the development of 5G with more than €4 billion in two ways. Via the budget, the EU funded research-only projects, while the European Investment Bank (EIB) supported both research and deployment, making it the EU's largest provider of funding for 5G-related projects. By August 2021, the EIB had granted loans totalling €2.5 billion for nine 5G projects in five Member States. In addition, around EUR 1.9 billion was made available from the EU budget in 2014-2020 (European Court of Auditors, 2022, pp. 11-12).

In Europe, total telecommunications investment in 2021, expressed by capex, reached €56.3 billion, its highest level in Europe since 2016 (Figure ++). Nevertheless, Europe continued to trail other major markets. In 2021 investment per capita adjusted to GDP was €104 in Europe, €156 less than in Japan, €46 in the USA and €6 in China. The increasing amounts invested in upgrading the infrastructures, coupled with lower ARPU and revenues than their peers in other regions gave high capex intensity compared to global industry levels. Nevertheless, Europe continued to trail other major markets. In 2021 investment per capita adjusted to GDP was €104 in Europe, €156 less than in Japan, €46 in the USA and €6 in China. In 2022, Europe showed figures of capital expenditure per capita adjusted for GDP/capita (104 €bn) below their peers: 45.2 €bn, 155.3€bn, 13 and 6.2€bn less than in the USA, Japan, South Korea and China, respectively. The high capex intensity in Europe compared to global industry levels results in reality from the increasing amounts the telecommunications operators are investing in upgrading their infrastructures, together with lower ARPU and revenues than their peers in other regions (European Telecommunications Network Operators, 2023, pp. 14, 28; 31).

Another way of looking at this is to consider the ratio of capex to earnings before interest, taxes, depreciation, and amortization (EBITDA). In 2021, ETNO participants had the highest average capex to earnings before interest, taxes, depreciation and amortisation (EBITDA) margins (35.3%); slightly ahead of US operators (33.1%), easily ahead of Chinese peers (28.7%) and substantially ahead of Japanese and South Korean operators (26.7% and 20.8%, respectively) (European Telecommunications Network Operators, 2023, p. 32).

Large-scale content and application providers (CAPs) also invest in digital infrastructure. Now then, CAPs have so far invested almost nothing in European physical networks that are closer to end users than caches, and certainly nothing at all in European fixed access or the physical RAN. CAPs investment prioritises the data centres with approximately €16 billion in front of approximately €1 billion in a mix of transport networks (primarily very large international/subsea routes) and internet peering/direct transit and caching. (European Telecommunications

Network Operators, 2023, p. 35). While these points are interesting, we consider them to be neutral in explaining backwardness because Europe does not differ substantially from its peers.

6. Conclusion

This paper explores the factors influencing the deployment of 5G technology, with a focus on Europe. While the topic of 5G adoption is relatively contemporary and important, the discussion doesn't seem to bring entirely groundbreaking theories. However, the focus on Europe's unique challenges and comparisons with global peers, along with the detailed breakdown of technological, regulatory, and economic considerations, adds value. This makes it innovative in its specific focus rather than in presenting a novel theory or model.

The paper addresses a critical, ongoing technological transition that impacts various sectors globally, particularly in telecommunications, business, economics, and infrastructure. It's highly relevant to policymakers, academics, and industry leaders, particularly in Europe, where 5G deployment has faced delays compared to other regions. The research's implications for the future of global digital economies and technology policy make it significant. The objective of this research was to elucidate the factors influencing the design and utilisation of a novel technology. To this end, the constraints and conditions that determine the launch and deployment of 5th generation mobile telephony technology worldwide were examined. The research adopted a business perspective, emphasising economic and business issues. One factor, sometimes overlooked by specialists, has been examined in particular.

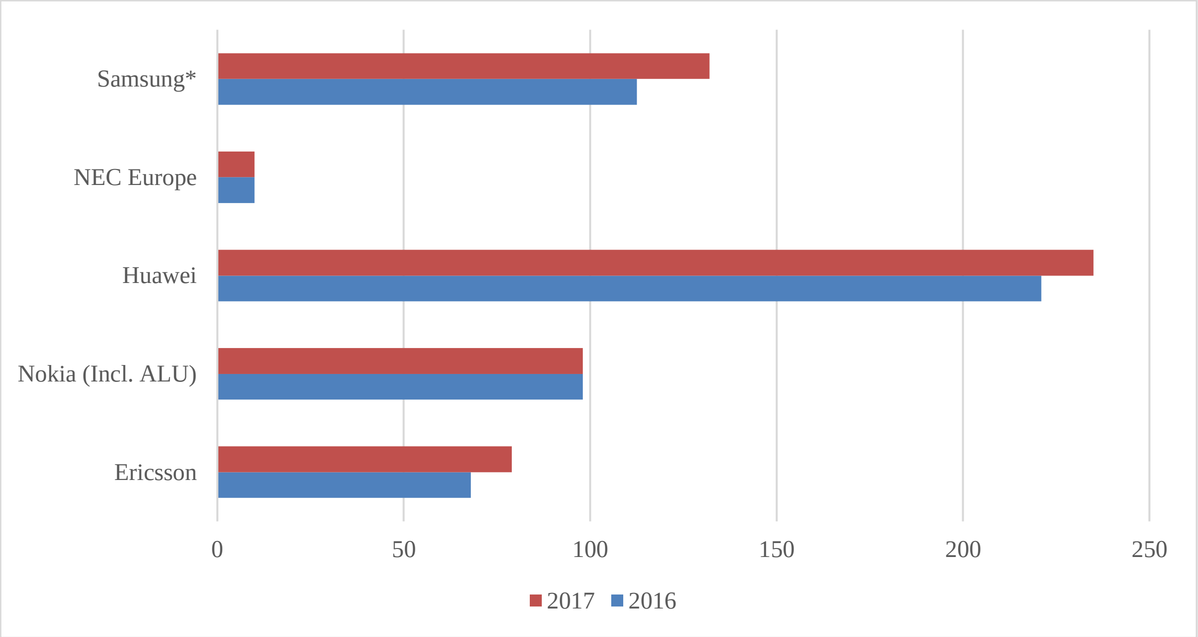
5G technology development involves several phases, including understanding system requirements, R&D, optimization, pilots, demonstrations, trials, and scalability testing. However, increased complexity and coverage density of 5G technology have led to higher costs. Alternative infrastructure ownership models, such as spectrum policy and network sharing agreements, can help reduce costs. Consolidating mobile networks and enabling interoperability between hardware and software vendors can also reduce fixed costs. Administrations promote network sharing agreements to reduce infrastructure costs by 16%-35%, consolidate mobile networks, and increase choice, competition, and innovation. All in all, it seems sensible to dismiss investment as an isolated determinant of European backwardness. Rather, we return to a multivariate explanatory scheme. To close the gap in 5G deployment, Europe must prioritize investments in R&D, streamline regulatory processes, and encourage greater collaboration between telecom operators and public institutions. Only through coordinated efforts can Europe regain its leadership in this crucial technological race.

In any case, it must be borne in mind that we are in the middle of a technology development process and that we still lack sufficient perspective.

Generations	Access Techniques	Transmission Techniques	Error Correction Mechanism	Data Rate	Frequency Band	Bandwidth	Application	Description
1G	FDMA, AMPS	Circuit Switching	NA	2.4 kbps	800 MHz	Analog	Voice	Let us talk to each other
2G	GSM, TDMA, CDMA	Circuit Switching	NA	10 kbps	800 MHz, 900 MHz, 1800 MHz, 1900 MHz	25 MHz	Voice and Data	Let us send messages and travel with improved data services
3G	WCDMA, UMTS, CDMA 2000, HSUPA/HSDPA	Circuit and Packet Switching	Turbo Codes	384 kbps to 5 Mbps	800 MHz, 850 MHz, 900 MHz, 1800 MHz, 1900 MHz, 2100 MHz	25 MHz	Voice, Data, and Video Calling	Let us experience surfing internet and unleashing mobile applications
4G	LTEA, OFDMA, SCFDMA, WIMAX	Packet switching	Turbo Codes	100 Mbps to 200 Mbps	2.3 GHz, 2.5 GHz and 3.5 GHz initially	100 MHz	Voice, Data, Video Calling, HD Television, and Online Gaming.	Let's share voice and data over fast broadband internet based on unified networks architectures and IP protocols
5G	BDMA, NOMA, FBMC	Packet Switching	LDPC	10 Gbps to 50 Gbps	1.8 GHz, 2.6 GHz and 30–300 GHz	30–300 GHz	Voice, Data, Video Calling, Ultra HD video, Virtual Reality applications	Expanded the broadband wireless services beyond mobile internet with IOT and V2X.

Annexe 1. Summarising the characteristics of the mobile technology

Source: Elaborated from Dangi et al., 2021, p. 3.



Annexe 2. 5G private R&D expenses by infrastructure vendors (as 2% of total R&D), €million

Source: Elaborated from The European 5G Annual Journal, 2017, p. 65.

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Notes

Note 1. 2G had three more versions (2.5; 2.75) since the 1990s; 3G four more versions (3.5; 3.75; 3.90 and 3.95) since the 2000s; 4G two more versions (4.5; 4.90) since the 2010s: Horner et al., 2023, p. 10. 4G allowed to communicate by connecting devices to the Internet and increased the transmission rates from 64kbps to 100Mbps: Frauendorf and Almeida de Souza, 2022, p. 84. Fourth Generation LTE-A (4.5G) is an advanced version of standard 4G LTE, which uses MIMO technology to combine simultaneously multiple antennas for both transmitters as well as a receiver, making LTE-A three times faster than standard 4G: Dangi et al., 2021, p. 1.

Note 2. Nevertheless, in the introduction of 3G and 4G, the operators' prominent co-ordination role in terms of timing and functionality, as seen in the previous standard, has been de-emphasised. This stemmed from the expectation that the competitive market would drive the roll-out process, while the operational aspects of the new generation are now being handled by the GSMA, the institutional successor to the previous Memorandum of Understanding between operators: Lemstra, Cave and Bourreau, 2017, pp. 22-23.

Note 3. The potential for sharing wireless infrastructure to reduce deployment costs exists throughout all aspects of the network. Infrastructure sharing initiatives commonly include network-infrastructure sharing between complementary networks, revenue sharing between cell site, backhaul providers and operators, and partnerships with electric utilities and railways to enable network expansion (International Telecommunication Union, 2021, pp. 6-7).

Note 4. Several policy makers have advocated commercially-driven network sharing agreements as a means to substantially cut network build costs. While passive network sharing was commonplace for 3G and 4G deployments, more active network sharing has been deployed for 5G, particularly amongst the major European MNOs: KPMG, 2019, p. 3.

Note 5. An example of evolutionary path to 5G: Ericsson, 2019, pp. 1-9.

Note 6. Maule et al., 2020, p. 2. While significant progress was achieved for Core Network Slicing, a key technology enabler for advanced connectivity and data processing, Radio Access Network (RAN) slicing still presents limitations in terms of sharing infrastructure, Service Level Agreement guarantees, isolation, resource scheduling and allocation. Think of 5G’s network slicing as creating different lanes on a motorway. Some lanes are designed for fast cars (high data traffic), while others are for trucks (devices requiring less data). This ensures smoother traffic flow and greater efficiency for all vehicles.

Note 7. Let's take a few milestones for Verizon. Since 2017, the operator began testing mm-wave 5G service in eleven cities. In summer 2018, together with Nokia, achieved both a 5G NR signal to two moving vehicles and 5G signals in commercial trials in Washington, DC and Minneapolis with the prototype believed to be the first commercial 5G service, over its proprietary 5GTF network standard. It offered Fixed Wireless Access (FWA) broadband -in fact a pre-standard version- for home connectivity in parts of four large cities. Verizon's network was based on the 28 GHz spectrum, which suits rapid data downloads but not coverage of large areas: Blackman and Forge, 2019, pp. 13-15.

Note 8. Combinatorial Clock Auction has a “package bidding in two stages: first, a clock auction; then a single round of sealed supplementary bids when each bidder can make mutually exclusive bids on as many different packages as it wants, but at most only one of these bids can win, and payments by the winning bidders are set according to a second-price rule”: Myers, 2023, p. XVII. Complex auctions such as CCA lead to bidders engaging in predatory bidding. 4G CCA auctions in Austria, Switzerland and UK all led to high prices and highly asymmetric outcomes: Jacobs, Cordova and Associates, 2020. Open auction leads to mutual competition but collusion appears easily because each participant is allowed to deliver information; simultaneous auction: bidders offer a price for some goods from a specific spectrum; English auction: the price starts off low, and the buyers' bid-up price is until no one is willing to bid higher; Dutch auction starts off high and the price decreases until someone bids: Dang and Li (2022), pp. 181–185.

Note 9. For example, in France nearly 70 left-wing and ecologist elected representatives called on the government to impose a moratorium on the rollout of 5G, while calling for "a decentralised democratic debate" (*Le Journal du dimanche*, 13 September 2020; *Le Monde*, 13 September 2020.

On occasion, companies have been forced to reject conspiracy theories which linked the spread of COVID-19 to 5G or to mobile technologies and incited individuals to damage masts and base stations in a number of countries (Vodafone Group Plc., 2020, p. 50). Incidents in the UK: *New York Times*, 10 April 2020. https://www.nytimes.com/2020/04/10/technology/coronavirus-5g-uk.html.

Note 10. See the country profile in OECD (2018).

Note 11. Some big powers had low levels of connectivity: in 2017, France, for example, ranked 20th among EU Member States: European Digital Progress Report (EDPR) 2017, p. 4.