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Conference Paper

Evolution of prices for mobile spectrum & possible explanations

24th Biennial Conference of the International Telecommunications Society (ITS): "New bottles for new wine: digital transformation demands new policies and strategies", Seoul, Korea, 23-26 June, 2024

Provided in Cooperation with:

International Telecommunications Society (ITS)

Suggested Citation: Ihle, Hans; Marsden, Richard; Frizlen, Yasmine (2024) : Evolution of prices for mobile spectrum & possible explanations, 24th Biennial Conference of the International Telecommunications Society (ITS): "New bottles for new wine: digital transformation demands new policies and strategies", Seoul, Korea, 23-26 June, 2024, International Telecommunications Society (ITS), Calgary

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Evolution of prices for mobile spectrum & possible explanations

Working Paper - prepared for the 24th
ITS Biennial Conference in Seoul (2024)

9 June 2024

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1. Introduction

The adoption of 4G and 5G technologies has led to a remarkable surge in mobile data consumption, prompting regulators worldwide to make substantial amounts of new spectrum available to mobile operators through spectrum auctions. This paper aims to examine the trends in spectrum pricing and to address the question of how much spectrum mobile networks will need in the long term.

Spectrum auction prices should reveal the market value of spectrum which will provide an indication of its scarcity. Therefore, to address this question, the paper utilizes a global dataset of more than 400 spectrum auction prices from 2007 to 2023 to demonstrate that spectrum prices have generally declined over the past two decades. This decline suggests that while mobile data traffic has expanded, the release of new spectrum has generally kept pace and helped avoid capacity issues on mobile networks.

In Section 2, we¹ examine the trends for different types of spectrum, including low band, lower mid-band, and upper mid-band spectrum, which serve different purposes in mobile networks. The results indicate an overall decline in spectrum prices, with the steepest decline observed in low-band spectrum. This suggests that incremental coverage spectrum is no longer essential, as successive releases of this spectrum have adequately met market demands. Lower mid-band spectrum prices have also decreased, while prices for upper mid-band capacity bands have remained relatively stable, indicating their continued importance in providing capacity.

In Section 3, we turn to mobile data consumption. Industry statistics generally show an accelerating growth rate in the early days of 4G, but a decline in the later 5G era. A possible implication is that data consumption is following an S-shaped curve typical for technological innovation. We fit a generalized logistics function to OECD data using least squares and then use it to forecast mobile data demand in the future. These forecasts are then compared to other projections which assume exponential growth. We find that the S-curve provides a more plausible path for mobile data growth, based on historical data, implying that exponential forecasts significantly overestimate future data consumption. Higher growth forecasts may only be justified if there is a significant future change in how we use phones, such as widespread adoption of data-intensive extended reality (XR)² technology,

This finding has significant implications for regulators planning future spectrum releases. Even with slowing data growth, the absolute expansion in data traffic carried by mobile networks over the next ten years will be substantial. Nevertheless, it may be possible to accommodate this with relatively modest increases in spectrum allocation for mobile, as opposed to the huge increases that would be required to support exponential growth in mobile traffic.

¹ This paper builds on prior work by the authors, published as Chapter 10 of Marsden, R., 2024, "Round-by-Round, Learnings from the First 35 Years of Spectrum Auctions", NERA.

² XR is an umbrella term for technologies that combine the physical world with digital elements to create immersive experiences. XR includes augmented reality (AR), virtual reality (VR), and mixed reality (MR).

2. Declining spectrum prices

2.1. Data

We have analyzed more than 400 spectrum auctions from 2007 to 2023 and have found that prices have generally declined over the past two decades. We first describe the changes in spectrum prices and then offer some possible explanations for the decline. We focus our analysis on prices from spectrum auctions. Competitive bidding in auctions should reveal the market value of spectrum, so our analysis allows us to estimate the relative scarcity of spectrum over this period.³

2.2. Findings

Although spectrum regulators around the world award similar frequency bands to support the same downstream mobile services, the prices paid for equivalent bandwidth can vary hugely between awards, both within and across countries. Such local variations may be explained by many factors, such as differences in spectrum supply and demand, the level of reserve prices, auction rules and the actions of specific bidders. This makes for a noisy sample. Nevertheless, when aggregating price data across our large sample of spectrum awards worldwide, it is possible to discern distinct global trends over time.

From the 4G era onwards, there has been a significant increase in the number of spectrum bands allocated to mobile and the range of frequencies used by mobile operators. This increased volume makes it possible to explore trends in prices for different categories of spectrum based on frequency.

Mobile spectrum bands can be grouped into the following four categories:

1. **Low band** (600, 700, 800, 850 and 900 MHz). These bands are recognised as particularly valuable, owing to limited supply and superior propagation: signals travel further and penetrate buildings more easily. They provide both capacity and broad geographic coverage. The 850 and 900 MHz bands were the first mobile bands, whereas 800, 700 and 600 MHz are newer bands progressively added in various countries between 2008 and today.
2. **Lower-mid band** (1800, 2100, PCS and AWS). These bands were the first mobile capacity bands, released from the late 1990s through late 2000s. They are not as effective for wide-area geographic coverage as low band spectrum, owing to weaker signal penetration. However, they collectively offer greater size and capacity, making them ideal for 3G and 4G deployment, especially in urban areas where signal propagation is less of

³ We exclude beauty contests and direct awards as the associated spectrum fees are set in advance by the regulator and are thus less informative with regards to the market value of the spectrum.

a concern owing to the need to re-use frequencies in increasingly dense cell site networks.

3. **Upper-mid band** (2300, 2500 and 3500 MHz). These bands were added later, providing operators with significant additional capacity for 4G and 5G deployment. Advances in mobile technology and densification of urban networks have made these bands more attractive over time.
4. **High band** (mmWave spectrum at 24, 26, 38 and 40 GHz). These bands are identified for deployment of 5G in urban centers and traffic hotspots. They offer huge capacity but limited propagation.

The three lines in Figure 1 track the evolution of unit (per MHz-pop) prices for the first three categories of mobile spectrum bands from 2010 to 2023.⁴ Again, we use a three-year moving average, so as to smooth trends and address low sample size for some categories in specific years.⁵

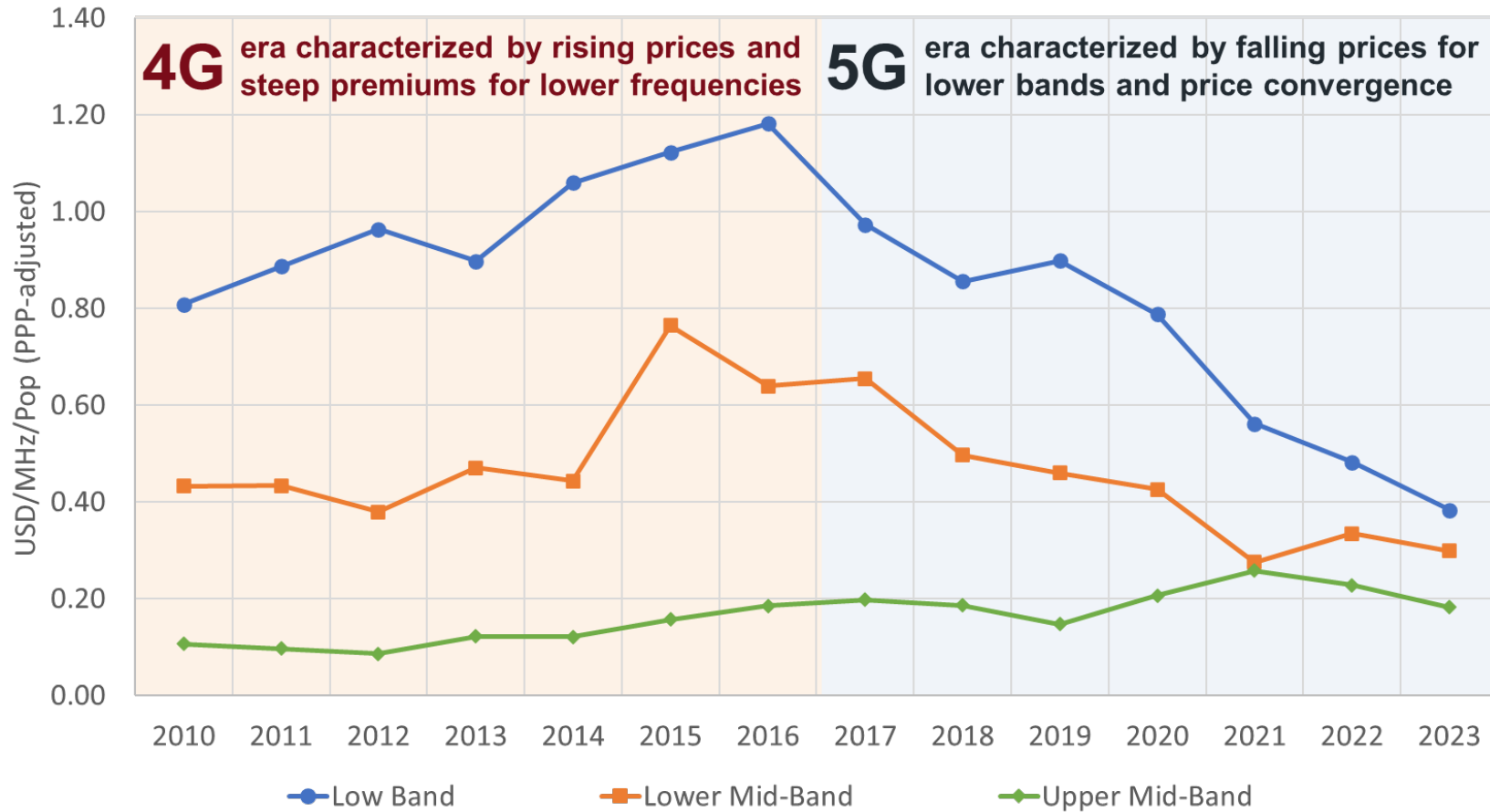
Unit prices paid for low band and lower-mid band spectrum exhibit an upward trend in the 4G era and downward trend in the 5G. However, prices paid for upper-mid band spectrum have evolved differently. In the 4G era, prices also rose but at a more modest pace than lower frequencies. This upward trend continued in the 5G era, with a notable lift from 2019-2021 and only a slight dip from 2021-2023.

Comparing prices paid across the different categories in the 4G era, it is evident that bidders were willing to pay a steep premium for lower frequency spectrum. In most years between 2010 and 2016, low band has sold at a 2X (100%) premium over lower-mid band, which in turn has sold at a 3X to 4X premium over upper-mid band. However, in the 5G era, these premiums have evaporated (as illustrated by the convergence of the three lines in Figure 1). Average unit prices paid for low band and lower-mid band are now quite similar, and the premium paid over upper-mid band is only about 2X. We attribute price convergence to a combination of data growth and technological progress which has led to an increasing emphasis on the high-capacity 2300, 2500 and 3500 MHz bands in 5G network rollout.

⁴ We ignore high band spectrum because there have been relatively few awards, and the equipment ecosystem is not yet mature (spectrum volumes are also very large and prices low compared to other bands).

⁵ Care should be taken in interpreting individual data points, as these may be quite sensitive to the impact of individual awards, especially high-price ones. An illustration of this point is that the 2015 peak of lower mid-band prices would have been visibly lower (at 0.61 \$/MHz/pop rather than 0.76 \$/MHz/pop) had we excluded the **USA AWS-3 auction (2015)** and **Canada AWS-3 auction (2015)** from the sample.

Figure 1: Three-year moving average of unit prices (USD) for categories of mobile spectrum, 2010-2023



Source: Adapted from Figure 31 in Marsden, R., 2024, "Round-by-Round, Learnings from the First 35 Years of Spectrum Auctions", NERA.

Notes: Data derived from survey of prices for all usable mobile spectrum sold in bands between 600 MHz and 4 GHz in 334 awards across 51 countries from 2008 to 2023. Spectrum prices include award revenues and the net present value of associated annual fees. They are converted to US dollars using PPP exchange rates from the World Bank and adjusted pro rata for a common license duration of 15 years.

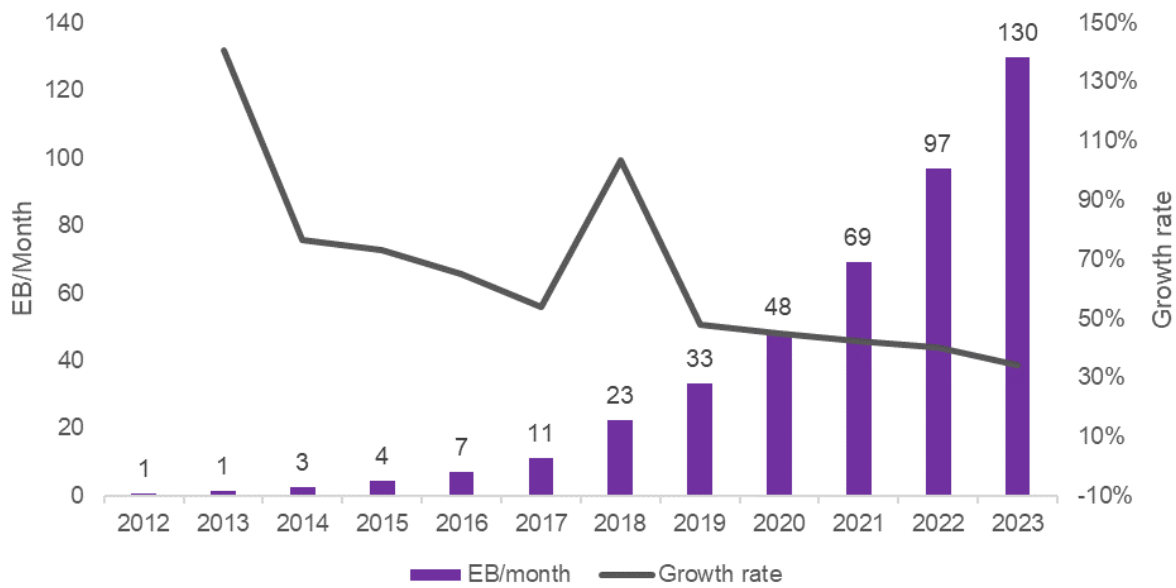
These price changes point to broader shifts in supply and demand for spectrum over time. Each wave of new technology has increased choice and volume of spectrum suitable for mobile. The rise in low-band and lower mid-band prices in the 4G era can be linked to escalating concerns about inadequate supply through to around 2015 coupled with exponential growth in mobile data demand. The subsequent decline of prices in the 5G era can be linked to the huge increase in supply and new technology enabling more efficient use of mobile spectrum.

2.3. Explanation A: Growth in mobile data demand has slowed

The decline in unit prices paid for spectrum has occurred even though demand for additional spectrum from mobile operators remains strong. Demand for MHz is ultimately underpinned by expected growth in mobile data traffic, which requires operators to expand network capacity. As illustrated in Figure 2, there has been explosive growth in mobile data traffic throughout the 4G and 5G eras, and most operators have responded by acquiring and deploying a lot more spectrum. The data growth rate has slowed in recent years, from around 70% per annum until 2018, to 34% in 2023. This is to be expected given the high monthly data consumption levels the market has reached. Even with these slower growth rates, 2021 and 2022 saw record increases in exabytes (EB) of data carried by mobile networks worldwide. The question is how quickly growth rates will slow over the coming years. For example, Webb (2018)⁶ forecasted that mobile data consumption will follow an S-shaped curve and plateau in 2027. We will investigate potential ways of forecasting mobile data growth assuming a generalized logistics function which has an S-shaped curve as well as simple exponential growth curves in Section 3. We show that the generalized logistics function fits the available data much better than the exponential growth curves and also produces more reasonable estimates of future mobile data consumption.

⁶ William Webb, 2018, *The 5G Myth: When Vision Decoupled From Reality*

Figure 2: Growth in global mobile data, 2012-2023



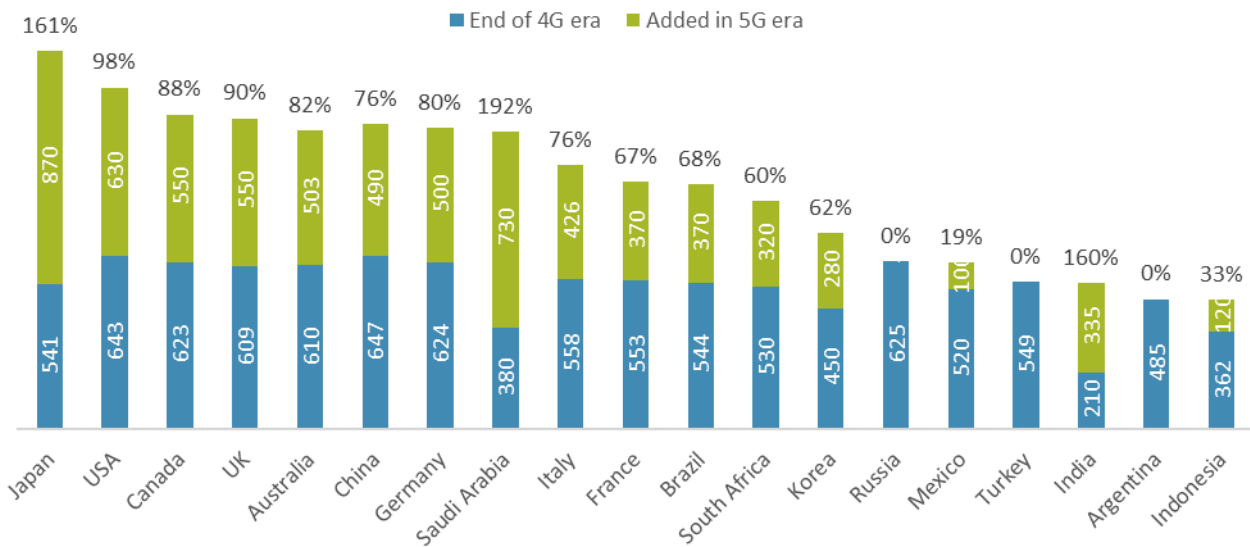
Source: Ericsson Mobility reports 2011 – 2023, available at: <https://www.ericsson.com/en/reports-and-papers/mobility-report/reports>. This chart was previously presented as Figure 33 in Marsden, R., 2024, "Round-by-Round, Learnings from the First 35 Years of Spectrum Auctions", NERA.

2.4. Explanation B: Supply has increased significantly

If demand for spectrum has risen but prices have fallen, then it must be that supply has increased sufficiently to offset rising demand, and this is indeed the case in many countries. Figure 3 summarizes the expansion in the supply of spectrum below 4 GHz across the G20 economies. This includes all low-band, lower mid-band and upper mid-band spectrum bands. We exclude high-band (mmWave) spectrum with its much higher bandwidth here as this type of spectrum will be used very differently to the other bands and is therefore not directly comparable.⁷ In most countries, supply has increased by 60% or more since 2017. This increase, combined with the densification of networks in urban areas to allow greater re-use of frequencies, is (in our view) the major factor explaining the decline in unit prices.

⁷ High-band spectrum is expected to be used in urban hotspots, stadiums and event spaces. It is unlikely going to be deployed as widely as the other spectrum bands.

Figure 3: Increase in low- and mid-band spectrum supply across G20 countries as of end-2023



Source: Figure 34 in Marsden, R., 2024, "Round-by-Round, Learnings from the First 35 Years of Spectrum Auctions", NERA.
Notes: Includes all awards in 4G era, 2009-2016, and 5G era, from 2017 to end-2023.

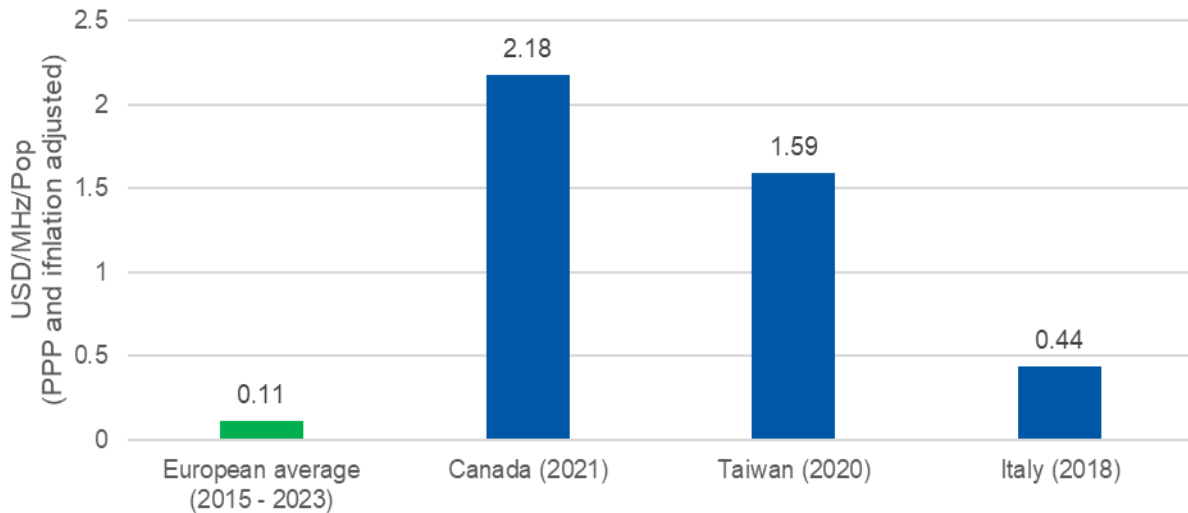
As NERA writing in GSMA (2017) highlight, high spectrum prices can often be linked to scarcity of spectrum. If the supply of a scarce resource is increased, its price (other things being equal) should fall. Although spectrum allocation for mobile is coordinated at an international level, countries follow different approaches and timelines to the release of frequency bands, often owing to challenges in clearing legacy users or differences in the development of local markets.

The impact of restricted supply on spectrum has become very apparent in recent auctions for 3500 MHz spectrum. Many countries, including a majority of EU states, have released around 400 MHz. With between 3 to 4 operators in a typical national market, this means that many operators have acquired at least 100MHz of spectrum, the maximum single carrier size for 5G as of 2023. Prices for spectrum in awards in countries with this structure have typically been modest, whereas countries that restricted supply have often seen much higher prices.

Figure 4 compares the average price paid for 3500 MHz spectrum in Europe with three awards where supply of 3500 MHz was constrained: **Canada 3500 MHz (2021)**, where only 200MHz was initially released or reconfigured and some spectrum was reserved for smaller players; **Taiwan 3500 MHz (2020)**, where only 270MHz was released and there are five mobile operators who all participated in the auction; and **Italy 3500 MHz (2018)**, where only 200MHz was released and the spectrum packaging prevented more than two of the country’s four operators from acquiring significant volumes. Observe that unit prices paid in Italy, Taiwan and Canada are between four and twenty times the European average for the same type of spectrum. This comparison illustrates the sensitivity of spectrum prices to the level and structure of supply in key frequency bands.

highlighted by the GSMA (2023)⁸, in some countries, set asides have curtailed the available supply of spectrum and contributed to higher spectrum prices.

Figure 4: Final Price per MHz per Pop (USD) paid for selected 3500 MHz awards



Source: Figure 35 in Marsden, R., 2024, "Round-by-Round, Learnings from the First 35 Years of Spectrum Auctions", NERA.

Notes: Same adjustments for license duration and exchange rates as Figure 1. In addition, we adjust for inflation and express figures here in 2023 prices.

2.5. Explanation C: Additional capacity did not lead to an increase in revenues per user

On the demand side, while mobile operators are chasing more spectrum, their willingness to pay is constrained by the ability to deploy that spectrum profitably. In the 4G era, there was significant optimism that growth in data traffic would be accompanied by the emergence of new revenue streams. However, as yet, these have not materialized. Instead, there has been a convergence of fixed and mobile communication business cases and commoditization of data. Owing to competition, fixed and mobile average revenue per user (ARPU) has declined 27% in the past ten years⁹. This decline has only partially been offset by modest increases in global mobile subscriptions.¹⁰ If spectrum supply is expanding and operators are not able to grow mobile revenues, then this impacts both the intrinsic value of incremental spectrum as well as operators' ability to pay for it. that both the intrinsic value of incremental spectrum is lower and also the willingness to pay for it is reduced.

Mobile operators also face considerable costs in building next generation networks. The continued spend on network deployments coupled with stagnant revenues and the fact that most mobile

⁸ GSMA (2023), The Impact of Spectrum Set-Asides on 5G, <https://www.gsma.com/connectivity-for-good/spectrum/wp-content/uploads/2023/06/Impact-of-Spectrum-Set-Asides-on-5G.pdf>

⁹ Accenture (2023), 'Pathways to profitability for CSPs', <https://www.accenture.com/content/dam/accenture/final/accenture-com/document/Accenture-Comms-Narrative-POV-final.pdf>.

¹⁰ Telegeography, Global subscriptions by Service, 2004 to 2022.

operators now have a good base portfolio of low, mid and higher frequency spectrum means that upcoming spectrum allocations are (typically) about incremental additions to spectrum portfolios rather than all-or-nothing events. This allows mobile operators to be more selective in their spectrum acquisitions.

These trends appear set to continue for some time, given expectations that mobile industry revenue growth will remain low. For example, GSMA Intelligence (2023) projects an average worldwide mobile industry revenue growth rate of only 1% per annum. It also forecasts that developing markets, which hitherto have enjoyed much stronger growth (from a low base) than developed markets, will see a sharp decline in growth between 2024 and 2026.

Although unit price reductions have been most pronounced for low-band spectrum, sub-1 GHz frequency bands remain of paramount importance to mobile operators owing to their ability to provide coverage in sparsely populated regions and deep indoor coverage within urban areas. The manner in which low-band spectrum has been allocated over the past 15 years has potentially contributed to the diminished value of additional spectrum bands. Low-band spectrum has been distributed in relatively narrow allocations, for instance, 2x30MHz each in the 800 MHz and 700 MHz ranges in Europe. Consequently, mobile operators are required to deploy new radio equipment for each added band, with limited capabilities for aggregating these bands to form larger, contiguous bandwidths for specific user services. This constraint places limitations on the capacity and speed that can be delivered over these bands, further exacerbated by the inherent limitations of lower Multiple-Input, Multiple-Output (MIMO) configurations imposed by antenna size.

In the 5G era, the emergence of new technologies, such as beamforming, massive MIMO, and the adoption of more aggressive indoor deployment strategies at higher frequencies have, for the time being, rendered additional investments in low-band spectrum less imperative. This is reflected, for example in the much lower prices paid for spectrum in Europe in the 700 MHz band, released in the 5G era, versus the 800 MHz band, released in the 4G era. Operators have instead been investing the bulk of their spectrum spend on larger quantities of mid-band spectrum which is complemented by network densification within urban and suburban areas.

2.6. Explanation D: The role of auction formats in influencing spectrum prices

The choice of auction format often has an impact on auction outcomes and prices.¹¹ However, taking a global perspective, it is hard to discern the impact of specific auction formats.

There have been very few attempts at establishing a statistical relationship between the choice of auction format and prices paid in spectrum auctions. One such attempt is Ihle et al. (2018) which found that open formats, such as the SMRA, CCA and Clock auction, produce higher prices on average than sealed bid formats. This is in line with economic theory: open formats provide bidders with feedback on their valuations and thus enable them to bid with confidence, leading to higher prices on average. Ihle et al. (2018) also found that the CCA produced higher prices than

¹¹ Marsden, R, 2024, "Round-by-round: Learnings from the first 35 years of spectrum auctions", NERA, p. 116-117.

other open formats. Interestingly, this effect is most pronounced (and statistically significant) for low-band (sub-1 GHz) spectrum which is scarcer than other types of mobile spectrum.

Regulators' preferences with respect to auction formats have shifted from the 4G era to the 5G era: use of the CCA has diminished and variants of the Clock auction have come to prominence.¹²

Given the link between the CCA and high low band prices, it is reasonable to infer that the growth in use of Clock auctions may have marginally contributed to the overall decline in observed prices for low-band spectrum in the 5G era.

¹² Marsden, R, 2024, "Round-by-round: Learnings from the first 35 years of spectrum auctions", NERA, see in particular chapters 5, 9 and 12.

3. Forecasting data growth

As described in Section 2.3, growth in mobile data demand is slowing. There is considerable uncertainty with regards to the future growth rate. This was, for example, acknowledged by Ofcom, the UK telecoms regulator in a Discussion Paper in 2022¹³. Ofcom at the time evaluated three growth scenarios:

- Low growth: 25% increase per year to 2030, 20% increase per year from 2030 – 2035
- Medium growth: 40% sustained increase per year to 2035
- High growth: 55% increase per year to 2030, 60% increase per year from 2030 – 2035

However, the most recent growth rate in the UK published by Ofcom of 23% from 2021 to 2022 is already below the 25% in the low growth forecast.¹⁴

In this section, we depart from these growth rate forecast and instead attempt to fit a generalized logistics function to mobile data consumption figures published by the OECD. We then use the estimated function to forecast mobile data consumption.

3.1. Literature review

Webb and Temple (2024)¹⁵ argue that the growth of mobile data traffic is slowing, suggesting that there may not be a need for further spectrum allocations for mobile networks. Industry statistics developed by Ericsson also identify slowing growth in mobile data.¹⁶ Ericsson generally shows accelerating growth rates in the early days of 4G, but a decline in the later 5G era. This suggests that data consumption may follow an S-shaped curve typical for technological innovation and may reach a plateau in the future.¹⁷ Oughton et al (2024) support this view claiming that many consumers are approaching a maximum quantity of video they can feasibly share and consume per day, and that as a result of this data growth is decelerating.¹⁸ The limited screen size of most mobile devices constrains the video quality required for an optimal viewing experience, so even with advances in video resolution, there may be a natural limit to how much data is consumed for mobile video.

¹³ Ofcom, 2022, Mobile networks and spectrum, https://www.ofcom.org.uk/_data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf

¹⁴ https://www.ofcom.org.uk/_data/assets/pdf_file/0034/264778/Communications-Market-Report-2023.pdf

¹⁵ Webb, W. & Temple, S., 2024, Emperor Ofcom's New Clothes: How the market approach to radio spectrum failed the country's mobile infrastructure and how to turn it around

¹⁶ Ericsson Mobility Report, <https://www.ericsson.com/en/reports-and-papers/mobility-report>

¹⁷ Pavlidou, A. 2010, Diffusion of the diffusion curve: A research on the S-curves in relation to technological clusters, Utrecht University, <https://studenttheses.uu.nl/bitstream/handle/20.500.12932/5743/A.Pavlidou-Final%20Thesis.pdf?sequence=1&isAllowed=y>

¹⁸ Oughton, E., Geraci, G., et al., 2024, Reviewing wireless broadband technologies in the peak smartphone era: 6G versus Wi-Fi 7 and 8, Telecommunications Policy, <https://www.sciencedirect.com/science/article/pii/S0308596124000636>

Using a different assumption, the GSMA¹⁹ and Bazelon & Sanyal (2023)²⁰ base their forecasts on exponential growth in mobile data. Another set of papers predict a stronger growth, such as forecasts from the ITU²¹ and Arthur D. Little²², which indicate continued exponential growth. Nokia (2024)²³ forecast that global mobile traffic will growth by 5X between 2022 and 2030, but a significant share of the growth beyond 2024 is attributed to mobile FWA and to take-up of XR.

The UK regulator, Ofcom (2022)²⁴, also uses largely exponential growth in its forecasts. We compare our projections for mobile data growth, based on a fitted logistics function, to those from Ofcom in Section 3.6.

Researchers have started exploring the implications of a continued decline in the growth of mobile data consumption. Oughton et al (2024), for example, urge spectrum managers to urgently reassess spectrum demand (which is a function of mobile data consumption) versus allocation. Webb and Temple (2024) draw similar conclusions, urging a refocus on ubiquitous quality coverage rather than continued expansion in capacity.

3.2. Data

We use data from 38 OECD countries for the time period 2011 to 2022.²⁵ As the data growth rates are noisy and appear to display regional variations, we have aggregated the data into four regional groups: North America, Western Europe, Eastern Europe and Northern Europe.²⁶ For each group, we population-weight the country data to obtain a representative average data consumption figure per year for each of these groups.

The results are presented in Figure 5 and Figure 6. Figure 5 shows the evolution of mobile traffic in GB and Figure 6 maps annual percentage growth in data traffic. Traffic levels are notably higher in Northern Europe, which may be attributable to combination of earlier adoption of mobile video and also a greater reliance on mobile rather than fixed networks for video consumption. With respect to data growth rates, these are high and noisy in the 4G period to 2016, but in the 5G era, growth rates clearly exhibit a downward trend, as described in Section 2.3.

¹⁹ GSMA, 2021, Estimating the mid-band spectrum needs in the 2025 – 2030 time frame, <https://www.gsma.com/spectrum/wp-content/uploads/2021/07/Estimating-Mid-Band-Spectrum-Needs.pdf>

²⁰ Bazelon, C. & Sanyal P., 2023, How much licensed spectrum is needed to meet future demands for network capacity, <https://api.ctia.org/wp-content/uploads/2023/04/Network-Capacity-Constraints-and-the-Need-for-Spectrum-Brattle.pdf>

²¹ ITU, https://www.researchgate.net/figure/Global-mobile-data-traffic-forecast-by-ITU-Overall-mobile-data-traffic-is-estimated-to_fig1_331159423

²² Arthur D Little, 2023, https://www.adlittle.com/sites/default/files/reports/ADL_Data_growth_Europe_2023.pdf

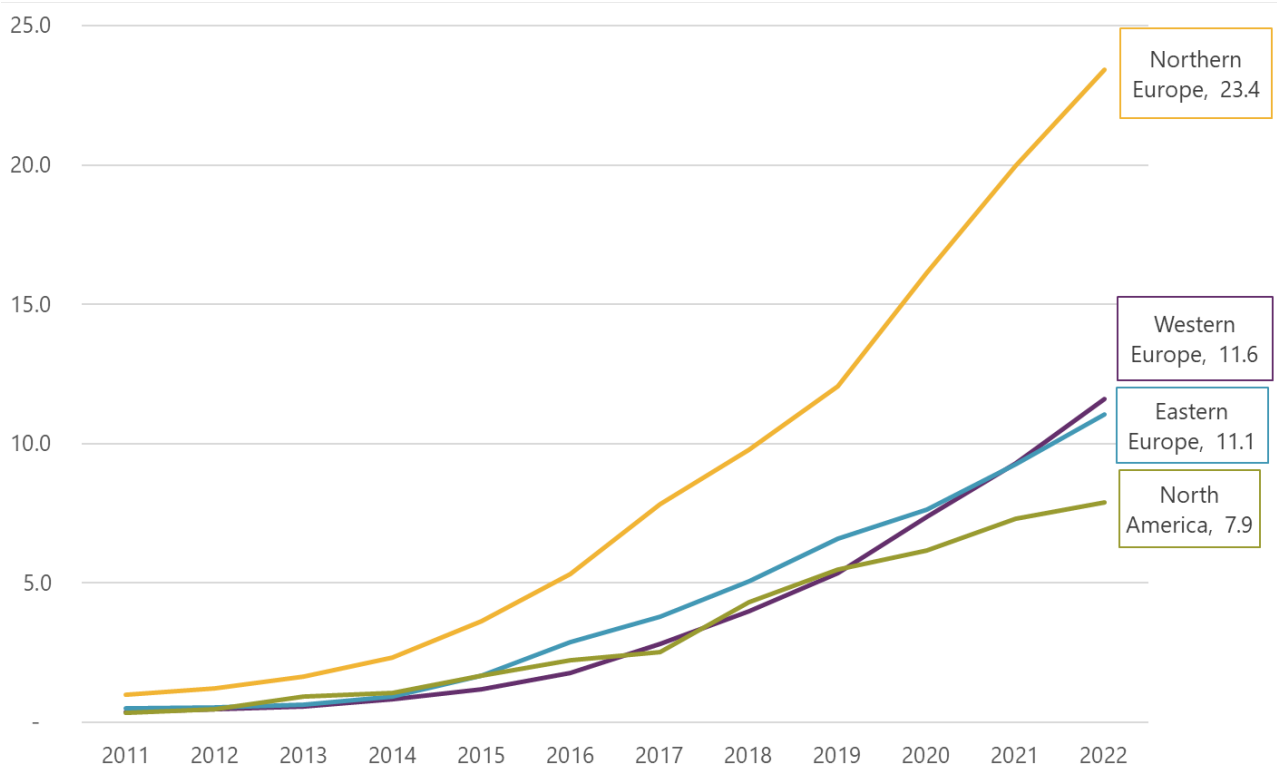
²³ Nokia, May 2024, Technologies to shape the 6G reality, presentation by Matthew Baker, Bell Labs Fellow, at the 6G Global Summit, London.

²⁴ Ofcom, 2022, Mobile networks and spectrum, https://www.ofcom.org.uk/_data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf

²⁵ <https://www.oecd.org/sti/broadband/broadband-statistics/>

²⁶ North America includes the USA, Canada, Costa Rica and Mexico. Western Europe includes Germany, Ireland, Portugal, Spain, Switzerland, Belgium, Italy, Austria, the UK, Luxembourg, the Netherlands and France. Eastern Europe includes Czechia, Poland, the Slovak Republic, Slovenia and Hungary. Northern Europe includes Sweden, Denmark, Latvia, Iceland, Norway, Lithuania, Estonia and Finland.

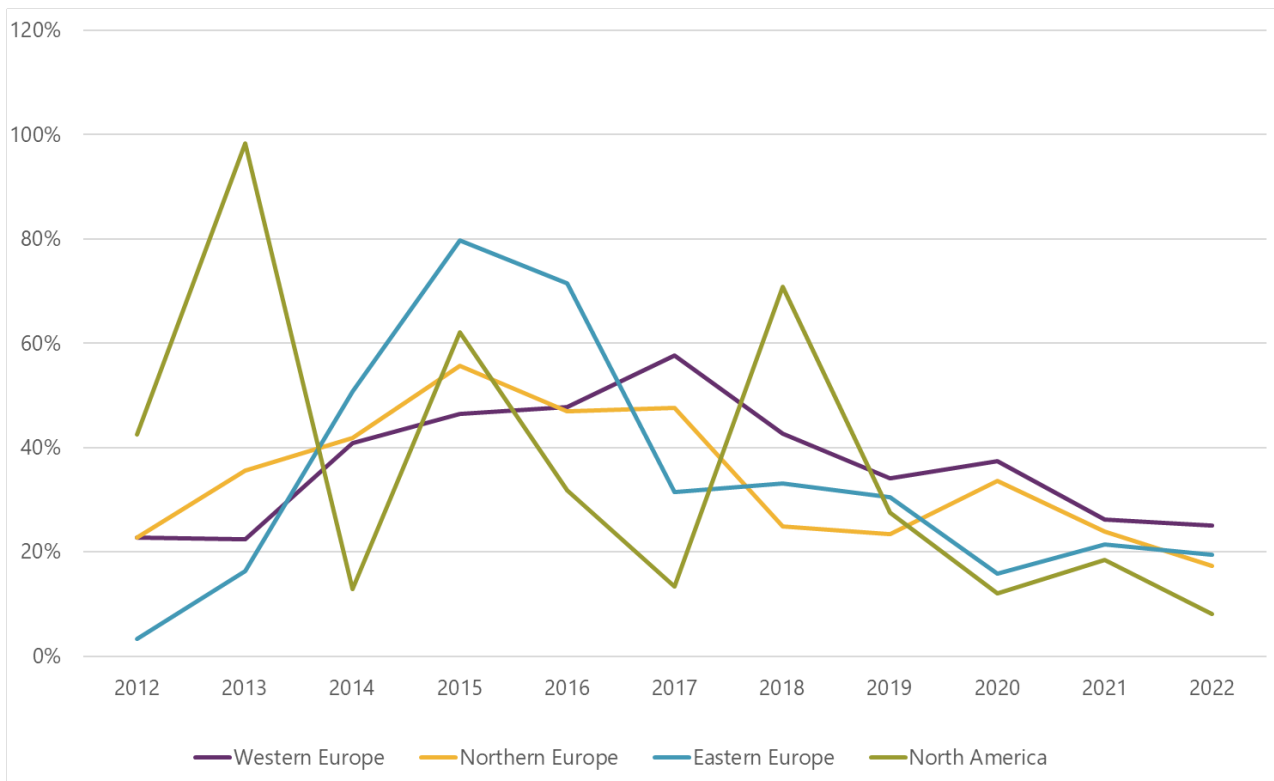
Figure 5: Mobile data consumption (GB per month per subscription)



Source: OECD data²⁷

²⁷ <https://www.oecd.org/sti/broadband/broadband-statistics/>

Figure 6: Mobile data consumption growth rates (% annual increase)



Source: Same as Figure 5 above.

3.3. Functional form of the S-shaped curve

The generalized logistics function exhibits an S-shaped curve which is often used to approximate the adoption of new technologies. The theory of diffusion of innovation on which it is based was popularized by Everett Rogers.²⁸ The fundamental model of innovation diffusion can be expressed by the equation:

$$N(t) = \left(\frac{1}{1 + e^{-k(t)}} \right)^a$$

where $N(t)$ is the cumulative numbers of adopters at time t

We fit this curve to the country-group level data as follows:

- We assume a common curvature of the S-curve across the different country groups, i.e. parameters a and k are the same across country groups. This implies that adoption follows a similar path across groups.
- We allow for a delay in adoption by adding an offset t_c term in the specification. This means that the adoption of mobile technology is not constrained to happen at exactly the same time in all country groups. The starting time period is 2011. We restrict t_c to no more

²⁸ Rogers, Everett (16 August 2003). Diffusion of Innovations, 5th Edition. Simon and Schuster.

than 3 (years), so that the adoption curve for any one country group can start anywhere between 2008 and 2011. We use 2008 as the earliest starting point as that is the year in which the iPhone was first released in most countries.

- We introduce a constant term c that can vary across country groups. This effectively represents the steady-state data consumption once full adoption has been achieved.

The final functional form for the data consumption $D(t)$ is thus as follows:

$$D_c(t) = c_c * \left(\frac{1}{1 + e^{-k*(t-t_c)}} \right)^a$$

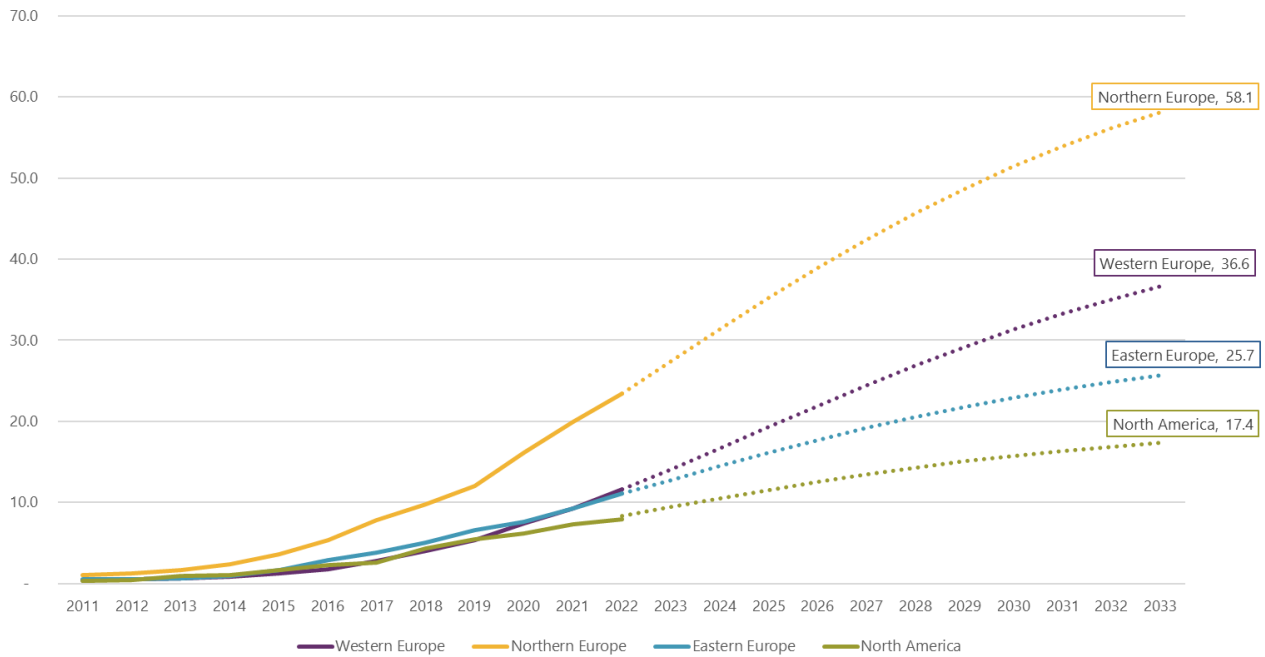
3.4. Estimation results

We fit the generalized logistics curve to the country-group level data. Our parameter estimates are shown in Table 1. The implied forecasts until 2033 for all four country groups are illustrated in Figure 7 below. We note that the final steady state consumption of mobile data varies considerably across these groups. This suggests that the current discrepancy we see across regional country groups in terms of mobile data consumption per device may persist into the future. In turn, this would imply that the higher traffic levels in Northern Europe versus the rest of Europe, and Europe in general versus North America, may reflect structural differences in the extent to which consumers rely on fixed versus mobile networks for data-intensive activities, primarily video consumption. Here, an important differentiator between country groups may be local take-up of mobile FWA, where the mobile network is used as a substitute for activities carried out elsewhere over fixed broadband connections. This can have a significant impact on mobile traffic as where consumers have access to fixed networks, they typically offload more data consumption over Wi-Fi. As the mobile FWA market is relatively new in many countries, this could yet impact significantly future growth rates and the top level of the S-curve. As our analysis in Table 2 suggests, the forecast implies that some country groups, such as Western Europe will see higher growth rates than others.

Table 1: Parameter estimates – Logistics function

	Joint	Western Europe	Northern Europe	Eastern Europe	North America
k	0.16				
a	5.92				
c_c		47	71	31	20
t_c		3	1.36	0.85	0
Sum of squared errors	2.69				

Figure 7: Actual and predicted future data consumption in GB/month per subscription



Source: Same as Figure 5 above.

Notes: 2011 – 2022 based on OECD data, 2023 – 2033 predicted data growth per mobile subscription based on estimates of the general logistics function.

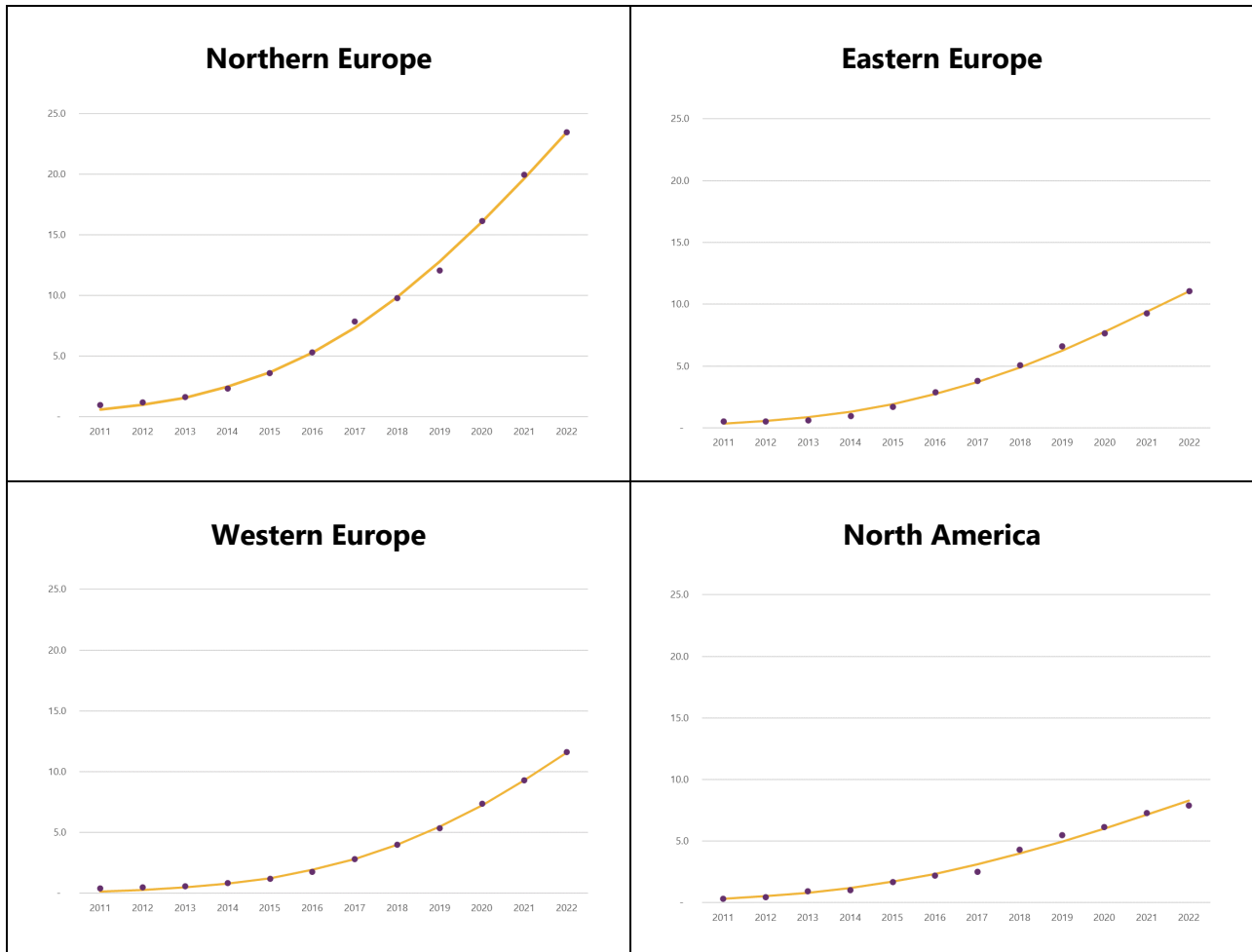
Table 2: Actual and forecast future data consumption in GB/month (using a general logistics function approximation)

	2022 (actual)	2025 (predicted)	2030 (predicted)	2033 (predicted)	Total growth
Western Europe	11.6	19.3	31.3	36.6	216%
Northern Europe	23.4	35.2	51.5	58.1	148%
Eastern Europe	11.1	16.1	22.9	25.7	132%
North America	7.9	11.6	15.7	17.4	120%

Source: Same as Figure 5 above.

We highlight the fit of our predicted values for the four country groups in Figure 8. The forecast methodology is able to capture growth at different points on the S-shaped curve for different countries. For example, Northern Europe seems much higher up the curve than Western Europe which also explains why the method still forecasts higher relative data growth in Western Europe than Northern Europe. An exponential growth function would not be able to mimic this result. Instead, it would cause the country group that starts at a higher mobile data consumption to diverge from a country group with lower data consumption.

Figure 8: Predicted vs. actual data consumption (GB/month)



Yellow: predicted, purple dots: actual values

Source: Same as Figure 5 above.

3.5. Comparison to exponential growth

We now compare our forecasts to an exponential growth model. Here we assume the following functional form:

$$D_c(t) = a_c * (g_c + 1)^t$$

Where g_c is the data consumption growth rate for each country group and a_c is the initial value.

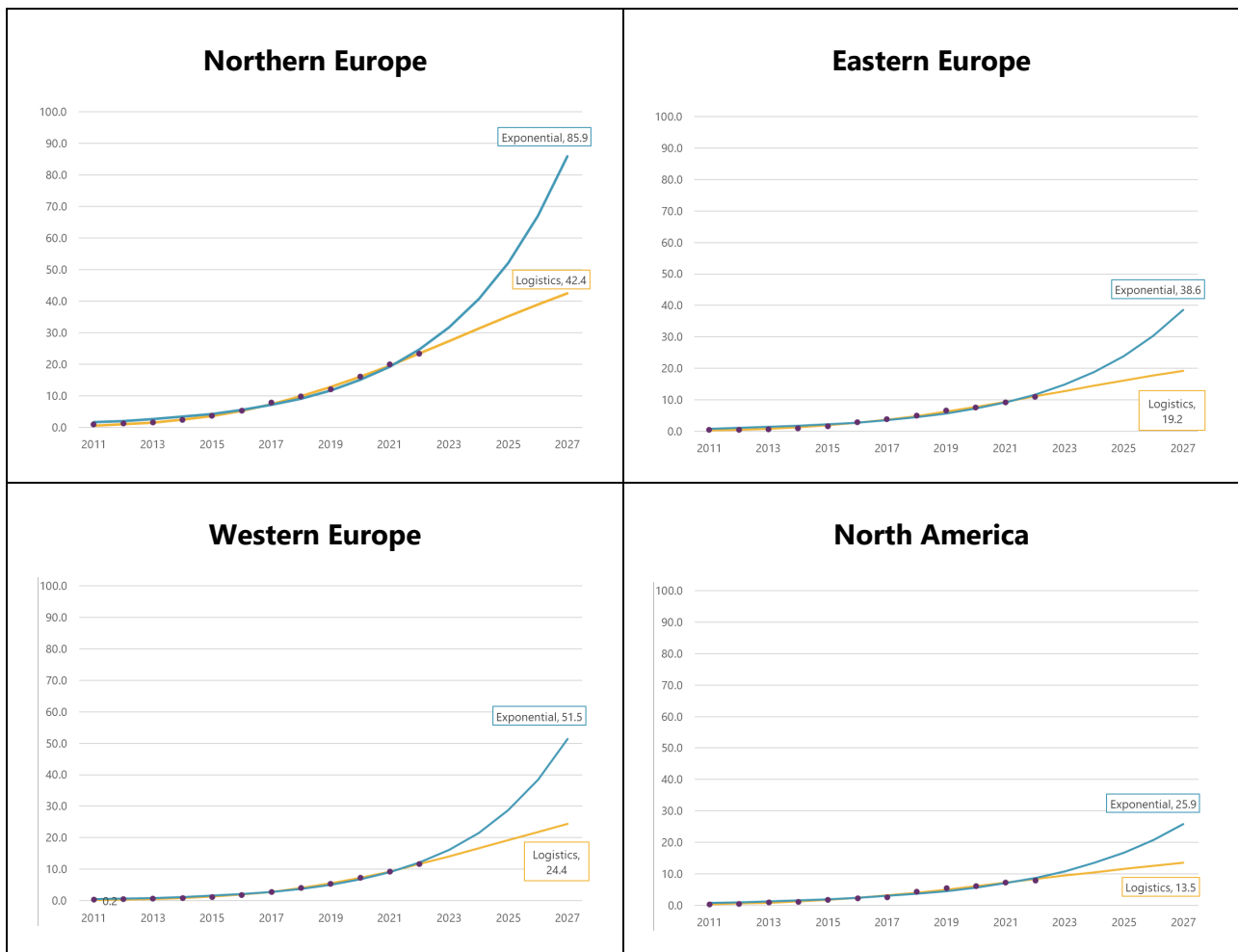
The parameter estimates are shown in Table 3. This model does not fit the data as well. The total sum of squares across all countries is 16.45, whereas the logistics function approximation results in a total sum of squares of 2.69.

Table 3: Parameter estimates – exponential growth

	Western Europe	Northern Europe	Eastern Europe	North America
a_c	0.5	1.6	0.8	0.8
g_c	0.34	0.28	0.27	0.24
Sum of squared errors	16.45			

In Figure 9 we highlight the results and compare them to the estimated logistics functions in the previous step. The fitted exponential growth functions produce reasonably close results in the past. However, in all four groups, we now observe a divergence of the actual values from the fitted exponential growth function. The logistics function approximation fits the data better in this respect. The longer term estimates are generally more uncertain, but the logistics function appears to produce more reasonable estimates given the longer-term trend of declining growth rates we observe.

Figure 9: Predicted vs. actual data consumption (GB/month per subscription)



Source: Same as Figure 5 above.

3.6. Comparison to Ofcom’s forecast

The estimates produced by the fitted logistics function mirrors certain voices in the industry speaking of a nearing plateau of mobile data consumption.²⁹ However, other estimations, such as Ofcom’s prediction ranges for data consumption, remain fairly constant³⁰.

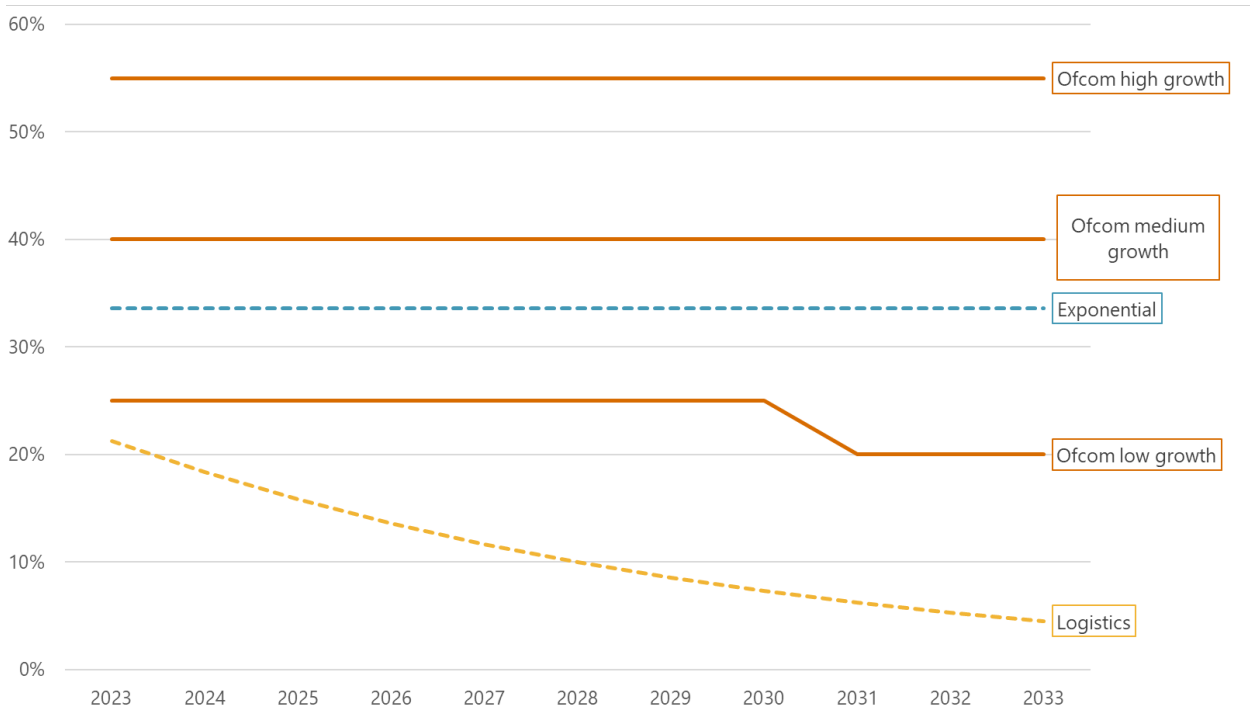
We now turn to a comparison of the growth rates predicted by the fitted logistics function (for Western Europe) and Ofcom’s forecast of the mobile data growth rate. Figure 10 compares the growth rate implied by the fitted logistics curve for Western Europe with Ofcom’s assumptions for

²⁹ William Webb. The end of an era of mobile data growth is in sight. <https://www.linkedin.com/pulse/end-era-mobile-data-grwoth-sight-william-webb/>

³⁰ Ofcom (2022). Ofcom’s future approach to mobile markets and spectrum – Consultation paper, https://www.ofcom.org.uk/_data/assets/pdf_file/0036/248769/conclusions-mobile-spectrum-demand-and-markets.pdf

the low-, medium- and -high-growth scenarios. The logistics rate is lower than any of the growth rates presented by Ofcom and is set to fall quickly over the next 5 years.

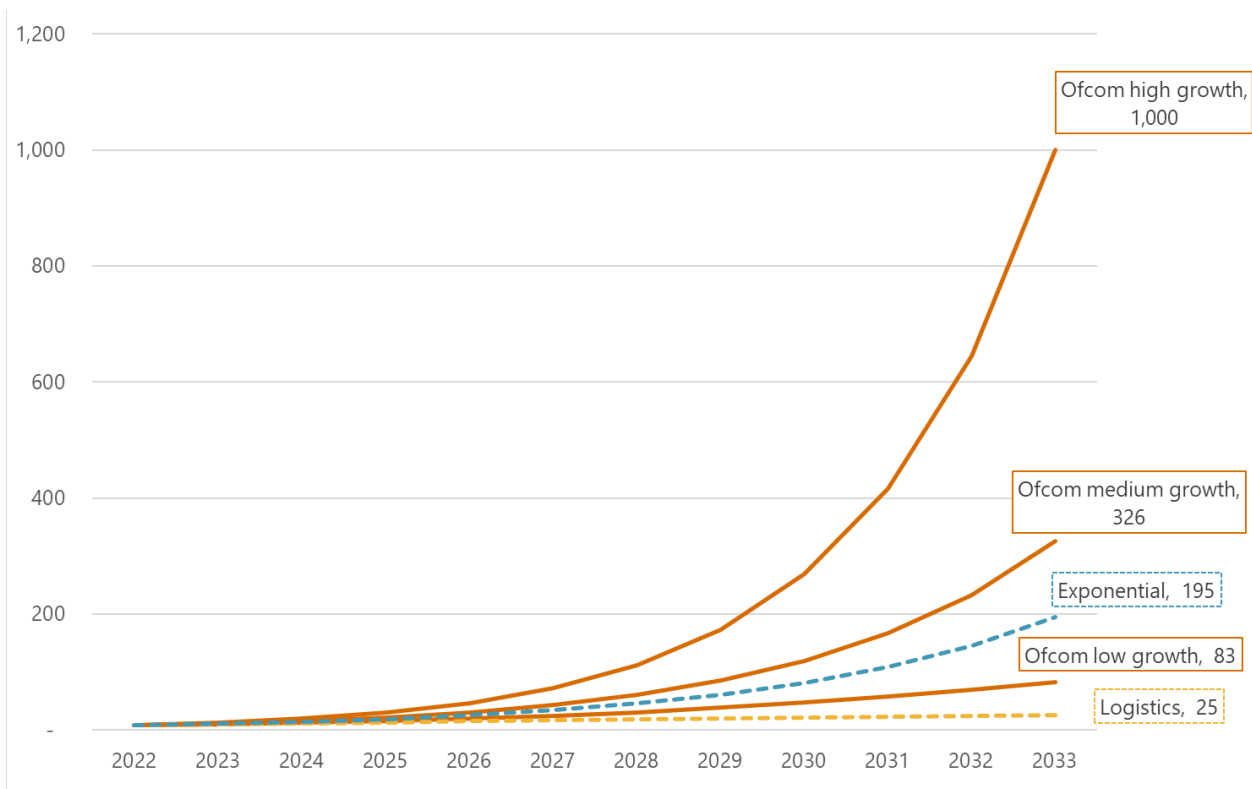
Figure 10: Comparison to Ofcom's growth rates



Source: Ofcom (2022) for Ofcom growth rates. Exponential growth rate and Logistics growth rate based on our estimates for Western Europe.

Forecasts based on exponential growth, regardless of whether low, medium or high, will surpass the estimated logistics growth by multiple factors over the next decade (see Figure 11). This is the case both for Ofcom’s set of prediction ranges, as well as for our own exponential growth function fitted to the group-level data for Western Europe.

Figure 11: UK data consumption forecasts in GB/month per subscription



Source: Same as Figure 5 above.

4. Discussion

Prices of spectrum, like any other good provided in a market, are ultimately determined by supply and demand. In the 5G era, regulators have been quite successful in adding large quantities of new mobile spectrum, which has facilitated a precipitous decline in unit prices. However, with mobile data consumption still increasing, albeit at a slowing rate, mobile operators are projected to require access to more spectrum by 2030, so prices may only remain low if regulators can find new sources of supply. Exactly how much additional spectrum will be required by the industry from 2030 is uncertain, but this will clearly be much less if growth does indeed follow an S-curve rather than exponential path.

Overall spend on spectrum has not diminished. Rather, it has been stretched across an expanding portfolio of spectrum bands, including increasing quantities of MHz at higher frequencies. Accordingly, further decline in unit prices paid for spectrum should be expected. Indeed, with operators under pressure to build new generation networks and revenue growth projected to be minimal, it is unrealistic to expect operators to be able to significantly increase their spectrum spend.

Technological advancements have led to a convergence in spectrum prices across different frequency bands below 4 GHz. The move away from the CCA may have accentuated this trend. Looking ahead, the outlook for spectrum prices varies across frequency bands. Early efforts to

identify spectrum for the 6G era have focused on higher bands at or above 6 GHz, but below mmWave. These new bands will be inferior substitutes for 3500 MHz. The scope to increase supply of low-band and lower-mid band spectrum appears more limited. Notwithstanding technological change, this should increase the relative scarcity of lower frequency bands, implying that their value may hold up better than higher frequencies. Accordingly, the current trend towards convergence of unit prices paid for mobile spectrum may not endure.

Given these trends, it is important that regulators be conservative when pricing releases of new and expiring frequency blocks for mobile as there is a substantial risk that historical price may overstate value.

The growth in mobile data demand is slowing. Rather than using an exponential growth function to forecast mobile data consumption, we think it would be more appropriate to use a logistics function. This provides a better fit to the data and produces forecasts that explicitly take account of the slowdown in growth rates. This approach should provide more realistic estimate of future mobile data consumption, and therefore a reasonable basis for projecting future mobile spectrum needs.

Regulators will need to be mindful that peak mobile data consumption, based on current trends in video consumption, could vary considerably by country, for example owing to different levels of substitution between fixed and mobile networks, including varying take-up of mobile FWA. It is also possible but speculative, that new data-intensive consumer technologies, such as XR, could take-off, creating conditions for a new period of exponential growth as the industry moves through the steep side of a new S-curve.



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