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"Welfare Cost of Mobile Spectrum (Mis)allocation"

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Welfare Cost of Mobile Spectrum (Mis)allocation *

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Abstract

Conditions under which spectrum is allocated are significant in determining the market structure in the telecom sector which in turn affects the prices and the quality of mobile services. In a more concentrated market, the quantity of spectrum is less diluted, and operators can offer higher quality to their customers; In a more competitive market, consumers can benefit from a lower price but at the expense of less quality for each operator. To address this trade-off, we first fit a demand model of mobile telecommunications services on a unique panel database of 23 European MNOs; we then conduct counterfactual simulations to measure the effect on consumer surplus of different schemes of spectrum allocation in Germany. Reallocating additional spectrum to three instead of four operators is consumer welfare improving as increasing prices is compensated by larger improvement in quality.

Keywords: *spectrum allocation; network investment; market structure; investment and competition*

JEL Classification: L40, L96, L11

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1 Introduction

Spectrum, while an essential element for operators, is a scarce resource and a valuable asset for the State. Also, the availability of additional spectrum or its reallocation is essential for the expansion and modernization of mobile broadband services. It is notably critical at the present time for the deployment of 5G networks and the services this technology will allow, especially for businesses.[1] In order to allocate this resource in the most efficient way and to raise revenue, the regulator can use different forms of auctions which can have significant effects in determining market structures in the telecom sector.

Now, the topic of how market structure affects pricing and the quality of mobile network is a recurring theme in the policy debates that have lately shacked the mobile telecommunications sector. Indeed, the total amount of spectrum in a country is limited and cannot be expanded. In its concern to maximize consumer welfare and take into account the economic utility of spectrum, the regulator is therefore in the middle of a trade-off between the quality and price offered to consumers: In a more concentrated market, the quantity of spectrum is less diluted, and operators can offer higher quality to their customers; In a more competitive market, where there are more operators, consumers can benefit from a lower price but at the expense of less spectrum for each operator.

To illustrate and address this trade-off, we focus on the German case. In Germany, out of a total of 4 bidders (T-mobile, Vodafone, O2, 11 Drillish), the auction for the allocation of 5G frequencies reached 6.55 billion euros in March 2019. Licenses are obtained if operators commit to achieve coverage obligations (namely, a minimum of 100 Mbps to at least 98% of households in each State by the end of 2022). In November 2019, German Federal Ministry for Economic Affairs and Energy opened a second phase during which private companies, from other sectors (energy, health, media, industry, transport ...), can obtain 5G frequencies. It was presented as a way for these companies to set up their own telecommunications structures to control the

[1] These services includes Enhanced Mobile Broadband, Massive Machine Type Communications or Ultra-reliable and Low Latency Communications.

security of their data and the reliability of their network.[2]

Our objective here is to provide a measure of effects on price and consumer surplus of the spectrum allocations that took place in Germany as part of the 5G auctions and to evaluate the outcome of alternative spectrum allocation by simulation. Note that the first scheme in the German process of spectrum allocation has involved the arrival of a new operator whose we evaluate the impact on the consumer welfare by looking at the spectrum redistribution it has triggered. Note also that the local assignments of spectrum allocation were incompletely implemented since part of the spectrum was not allocated at the time of the auction and so, could have been wasteful.

Using data from Strategy Analytics on prices and costs and from GSMA on coverages and associated spectrum, we first build a panel database for 23 MNOs of five major European countries from 2004Q3 to 2021Q4. Notably, we provide an adequate proxy of the mobile network quality for consumers by combining coverage data with spectrum data (the amount of spectrum owned by each operator) obtained from the GSMA Spectrum Navigator and consolidated using different reports from the regulators of the five countries included in the sample.

Second, we propose a demand model of the mobile telecommunications services. Thanks to this unique dataset, this model performs well in describing reality and allows us to precisely estimate the evolution of own-price and cross-price elasticities as well as marginal costs for each of the German operators during the period.

Third, we conduct a counterfactual simulation to measure the effect on consumer surplus of the incomplete spectrum allocation and the arrival of an additional operator, including the sharing of the 5G spectrum between four operators and not three. The outcome of these simulations are not straightforward. Indeed, while it is commonly believed that the entry of a new mobile operator improves competition, which may result in lower pricing and greater consumer surplus, the supposed positive entry impact might be reduced or even reversed if spectrum licensing

[2]This scheme is called "local assignment" and it refers to the allocation of spectrum to alternative actors to operators in a very limited area (therefore not at the national level unlike the operators) in order to develop applications and technologies based on 5G. In Germany, car manufacturers, logistics and transport platforms and university laboratories have been able to benefit from this local assignment for the 3700-3800 Mhz spectrum since November 2019. All the companies that have benefited from this local assignement are listed on the website of the German telecom regulator.

changes with the introduction of a new mobile operator. If a certain amount of 5G spectrum (50 MHZ) had been allocated to three operators equally, rather than four, our counterfactual simulations show that the consumer surplus would have been 3.8% higher, due to improved network quality. We also evaluate the effect of reallocating the local assignment of spectrum (100 MHZ) to operators (instead to alternative actors). The consumer surplus would have increased by 4% if this spectrum had been allocated to four operators, and by 7% if it had been allocated to three operators. It results that the relative increase in price is always lower than the relative improvement in network quality.

While our paper is aimed at proposing a simple framework to evaluate the welfare costs of different allocations of spectrum, it is clearly static in nature and is not intended to treat the question of incentives to invest. It only provides a measure of static efficiency, in line of what it is usually performed to evaluate the impact of mergers in competition policy for instance. In other words, it does not address the question of dynamic efficiency.

Our paper is related to the methodological field of structural differentiated-products oligopoly models, that was initiated by the seminal paper of Berry (1994) followed, among many others, by Verboven (1996), Berry *et al.* (1995), Ivaldi & Verboven (2005) and Nevo (2000). A crucial issue in this literature is the estimation of discrete choice demand models which is fully discussed in Berry & Haile (2021).

This paper also provides several contributions and is consistent with several fields of literature. First, it contributes to the economic analysis of the valuation of spectrum and to the literature studying the relationship between the allocation of mobile spectrum, consumers' valuations of spectrum, and market structure. We indeed propose a new measure of the quality offered to consumers based on the interaction between mobile coverage and quantity of spectrum owned by each operator that we include in our demand model; we also show that, in the case where the 100MHz of spectrum allocated to the local assignment would have been allocated to the operators, prices would have remained almost unchanged, while the consumer surplus would have been higher due to an improvement in the quality offered to users. One of the first contributions investigating the relationship between spectrum allocation and welfare maximization is Hazlett & Muñoz (2009). Focusing on mobile markets, the authors empirically estimate that countries allocating larger quantities of 3G spectrum, as well as allowing more intense competitiveness, realize demonstrable social welfare benefits through lower prices and conclude that auction rules intending to increase license rent extraction by restricting spectrum access are not welfare-enhancing. Kuroda & Forero (2017) compares the 3G mobile penetration rate in 47 countries with auctions or beauty test spectrum allocation process. They find that countries with auction allocation process have a lower 3G mobile phone penetration rates than those with beauty contest allocation process and suggest that auctions, when used to raise public revenues, sacrifice consumer surplus. Peha (2017) shows the existence of large economies of scale for MNOs when expending capacity, with MNOs minimizing cost by growing spectrum and tower holdings at similar rates. This allows a tradeoff between cost-effectiveness and market competition. The author concludes that according to a Pareto optimal assignment, spectrum should be divided fairly evenly regardless of whether the number of competitors is large or small. However, Woroch (2020) nuances the precedent results by empirically estimating the effect of spectrum concentration in the US wireless industry and showing a robust inverted-U relationship between spectrum HHIs and a measure of consumer welfare.

Our paper also adds to the literature on the link between market structure, investment and consumer surplus in the telecom sector. We find that, considering spectrum allocation and focusing on the joint effect on price and quality, the entry of a fourth operator in Germany has a negative effect on consumer surplus when compared to sharing the same amount of spectrum among three operators. In the recent literature, Motta & Tarantino (2017) show that, without efficiency gains, mergers reduce total industry investment and consumer surplus. However, if it entails sufficient efficiency gains, they might increase investments so much as to outweigh the usual detrimental effect of the merger on prices. Using a panel 33 OECD countries between 2002 and 2014, Genakos *et al.* (2017) studies the triple relationship between market structure, prices and investment in mobile telecommunications. The authors shows that more concentrated markets lead to higher prices but also to higher investment per mobile operator, although the impact on total investment is not conclusive. Using firm-level data, Houngbonon & Jeanjean (2016) investigates the relationship between competition and investment in the wireless industry. Subject to certain conditions, the authors find a robust inverted-U relationship between competition intensity and investment. Complementary to their precedent-setting work, Jeanjean & Houngbonon (2017) find that industry investment increases with the number of operators in the short run but falls in the long run due to significant adjustment costs of investment in the mobile industry.

However, let us note that, because the deployment of the 5G mobile technology is still very recent, empirical work on its effects on prices and on consumer valuation is still scarce. This is not surprising. In our study, consumers' "willingness-to-pay" only becomes positive and significant from 2021Q3 in Germany. While the deployment of 5G and the associated mobile offerings have been implemented since 2019-2020 depending on the European country, a positive valuation by consumers has been slow to be effective. This underlines the long delay for a mobile technology like 5G to be valued by consumers.

The remainder of this paper is organized as follows. Section 2 describes the data used in our study. Section 3 introduces our structural model of demand and our estimation strategy. Section 4 presents our estimation results. Section 5 presents the analysis of impact of hypothetical spectrum allocation change by counterfactual simulation. Section 6 concludes.

2 Data

2.1 Overview

Our analysis draws on two datasets at the operators' level having services in five major European countries (France, Germany, Italy, Spain and the U.K.) over seventy quarters from 2004Q3 to 2021Q4. The first dataset, obtained from Strategy Analytics, provides the average revenue per user (ARPU), the operational expenditure (OPEX) per user, the total number of active subscribers of each MNO[3]. The second dataset, from GSMA Intelligence, includes mobile network nation-wide population coverage for 3G, 4G and 5G technologies for each MNO. The coverage data is sourced directly from operators and regulators whenever they report 3G/4G/5G population coverage metrics (e.g., in financial statements, investor presentations and regulatory filings).

[3]The measure for OPEX (Operational Expenditure) is calculated by Strategy Analytics as the total mobile revenue minus EBITDA (Earnings Before Interest, Taxes, Depreciation and Amortization).

From these two datasets, we assemble an unbalanced panel data comprising 1241 observations on 23 MNOs.

Table 1: Summary statistics

Variable	Mean	Std. Dev.	Min	Max
Intra-MNO market share	27%	10%	3%	47%
ARPU (Euros/month)	19	7	7	43
Coverage3G (population)	83%	23%	8%	100%
Coverage4G (population)	44%	44%	0%	100%
Coverage5G (population)	4%	12%	0%	95%
Band_3G (MHz)	52	14	10	114
Band_4G (MHz)	46	51	0	210
Band_5G (MHz)	15	32	0	120
OPEXuser(Euros/month)	16	6	5	41
Year	2013	4.9	2004	2021

Table 1 reports the descriptive statistics for the variables used in the estimation. The total number of active subscribers to mobile services provided by each operator is the metric that is used to measure the market shares. It approximates the probability of a consumer to choosing a specific MNO among all possible MNOs. The mean value of 27% indicates that the number of MNOs is about on average three or four operators in European countries.

The average revenue per user (ARPU) is the price charged by MNOs, which is the income generated from all services divided by the total number of subscribers. When compared to consumer spending statistics, the ARPU has the advantage of being widely accessible for the five major European countries. This makes it possible to include 23 MNOs from the five countries in the econometric analysis, which is essential for the sake of statistical efficiency, robustness, and identification. The combination of the network coverage provided by MNOs and the related spectrum for 3G, 4G, and 5G technologies is used as a proxy for measuring network quality[4].

[4]An alternative of measuring network quality is the download speed provided by the data provider Ookla. Ookla has a platform that lets people who use mobile networks test their speeds. Users can test their mobile internet connection by downloading the Ookla application to their mobile phone. When a user runs a speed test, Ookla keeps track of operator, technology used and the average download speed. The Ookla data in our possession, does not cover all five major European countries nor the entire period 2004-2021. However, we have run some correlation tests in Appendix C between our interaction term (network coverage and associated spectrum amount for 3G/4G/5G) and the Ookla data (download speed, upload speed, and latency for 3G/4G/5G). We demonstrate that our interaction term is a reliable indicator of network quality.

The 3G coverage is higher than 4G since the latter has been deployed several years after 3G. Given that 5G is the most current technology and has only been deployed since 2019, the 5G coverage is still quite limited. As a scarce and expensive resource, the spectrum allocated to MNOs plays a key role in guaranteeing high levels of mobile network quality as measured by throughput.

Due to the fact that the quantity of frequency bands is fixed for each country, independent of the number of MNOs in the country, the amount of frequency bands per MNO reduces as the number of MNOs rises. For example, in Germany, the C-band around 3.6GHz has a fixed bandwidth of 300MHz reserved for German MNOs. 300MHz has been assigned to four MNOs, as shown in the bottom of Figure4, 90MHz to Vodafone Germany, 50MHz to Drillisch, 70MHz to Telefonica (O2 Germany), and 90MHz to Telekom Germany. In the absence of Drillisch, 300MHz of C-band could be divided among three MNOs, with each MNO receiving 100MHz. The variable OPEX per user is used as an instrumental variable to overcome the endogeneity of the price in the demand model below. It comes as no surprise that the mean value of OPEX per user is three euros less than the mean value of ARPU, as we can see in the statistics.

2.2 The German market

Since our simulations are focused on the situation of 5G spectrum allocation in Germany, we present several graphics that highlight the German mobile market to provide more detail of our data.

Figure 1: MNO's ARPU in Germany

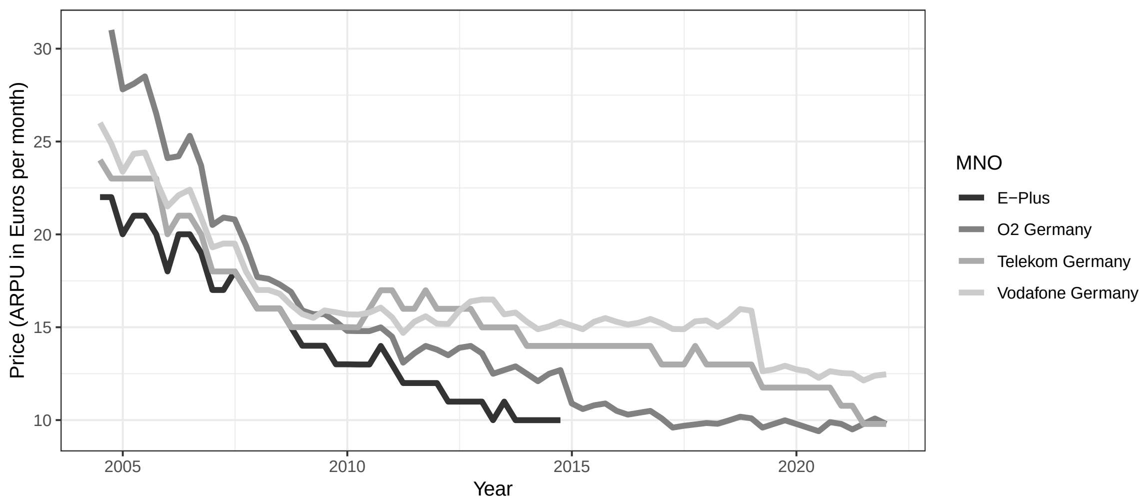

Figure 1 shows that ARPUs decrease over time. E-Plus had the lowest ARPU in Germany before its merger with O2 Germany in 2014.

Figure 2: intra-MNO market share (inside market share) in Germany

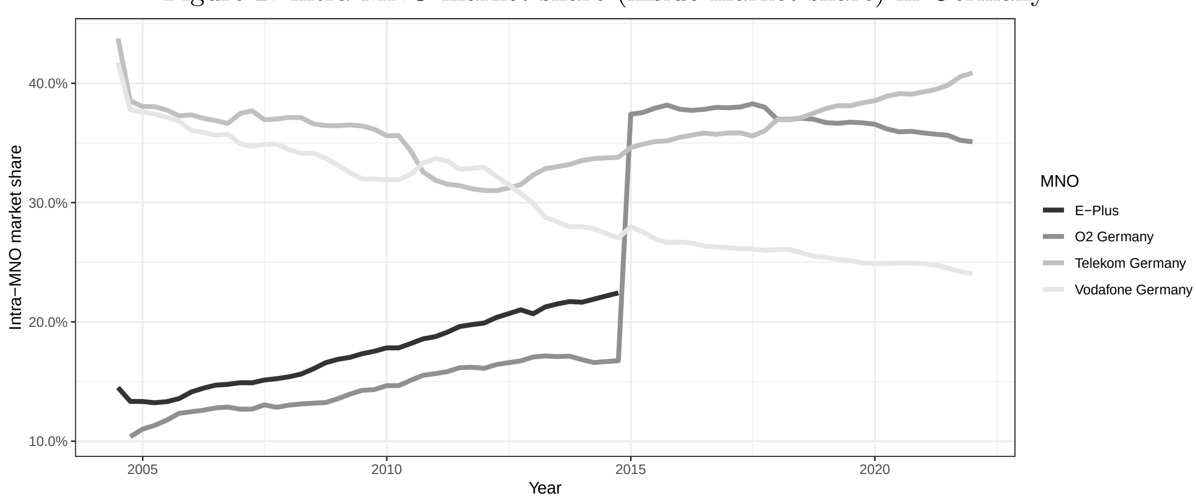

Figure 2 shows the change in intra-MNO market shares. Note that O2's market share surged initially after the acquisition of E-Plus in 2014, and then gradually dropped over time.

Figure 3: coverage of 3G/4G/5G by Telekom Germany in Germany

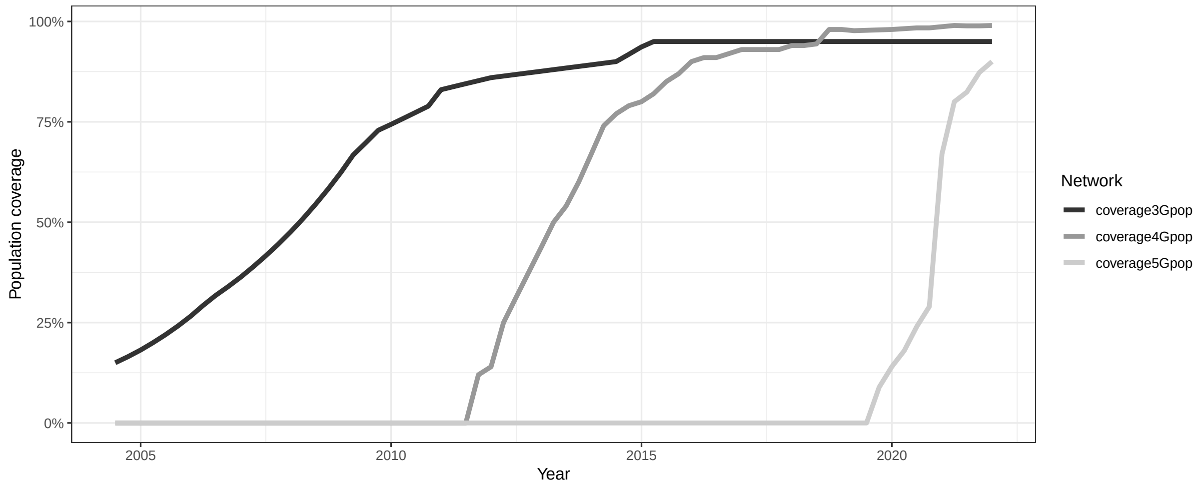

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Figure 3 depicts the progression of network coverage 3G, 4G, and 5G deployed by Telekom Germany. We can observe that the 3G required almost ten years to achieve full coverage. The 4G took just 4-5 years to develop. It only took 2-3 years for 5G to cover 90% of the population.

Figure 4: 2019 Spectrum auction in Germany

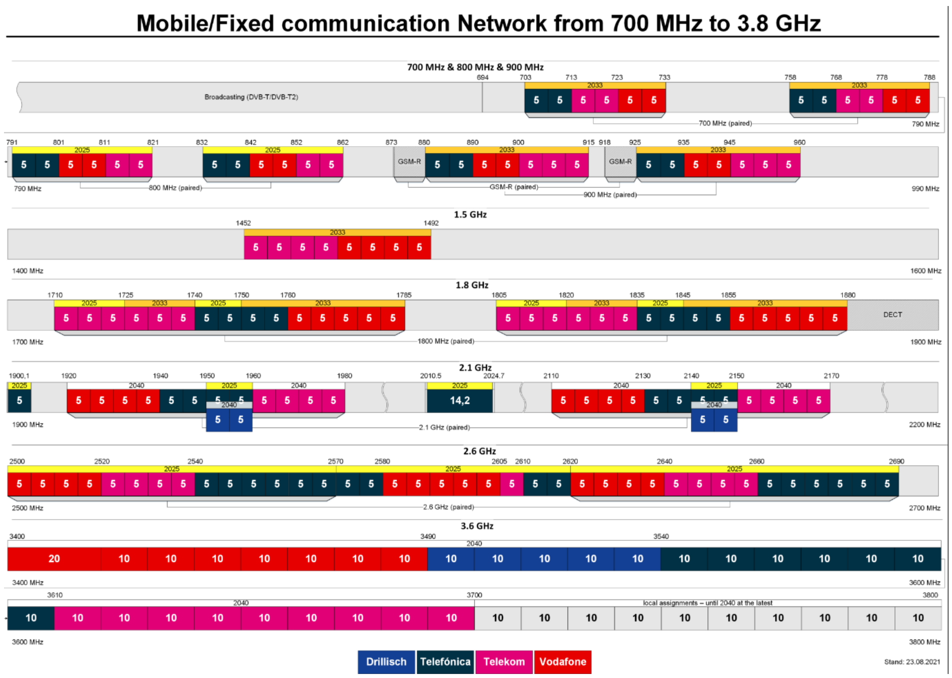


Figure 4 depicts the outcomes of 2019 German spectrum auction. The 5G spectrum allocation has two key features. First, Drillisch received 50MHz of C-band spectrum. Drillisch has planned to deploy their own 5G network using the 50MHz in the near future, with the objective of covering 50% of the population by 2030. Second, the German regulator has allocated 100MHz for local assignment. The objective is to develop regional business models such as industry and smart cities. These business models are still in their beginnings. Two simulation scenarios will be proposed based on these two features of the German spectrum auction.

3 A model of the mobile telecommunications market

In this section, we formulate an equilibrium model of the mobile market. On the demand side, consumers face a discrete choice of mobile operators' offers. On the supply side, mobile operators compete in prices, given their choice of mobile network quality.

3.1 Consumer's demand

As shown in Berry (1994), assuming that consumers choose the MNO with the highest utility and using the expression for the mean utility in Appendix (A), the choice probabilities at the aggregate level; can be equated to the market share. The demand model can be estimated by the following nested-logit regression of market share on MNO's network quality, prices and log-share terms related to the nesting structure:

$$ln\left(\frac{s_{jt}}{s_{0t}}\right) = \mu_0 + \beta q_{jt} - \alpha p_{jt} + \sigma ln(s_{j|gt}) + \xi_j + \xi_{jt} \tag{1}$$

where s_{jt} is the market share of operator j at time t, defined as the ratio of number of subscribers of operator j to the total market size[5]; s_{0t} corresponds to the share of the outside option (i.e. the choices other than the option to subscribe to an MNO offer, that is to say, MVNOs' subscribers and individuals without any subscription); q_{jt} is a vector of coverage and spectrum of mobile networks of technology 3G, 4G and 5G; $s_{j|gt}$ is the within-nest (intra-MNO) market share of operator j at time t in nest g, and p_{jt} is the price of operator j at time t, measured by ARPU (Average Revenue Per User).[6] As above-mentioned, the nesting parameter σ must belong to the interval [0,1]. If $\sigma = 1$, consumers perceive all operators of the same nest as perfect substitutes. If $\sigma = 0$, the model is equivalent to a simple logit model Note that the parameter α must be positive for the model to be economically meaningful.

In order to provide a good network quality, we need both a good coverage and sufficient spectrum quantity. It is obvious that a mobile network cannot work if one just has coverage and no spectrum, or if one possesses spectrum but no coverage. The term βq_{jt} is a linear combination of three terms corresponding to the three generations of mobile technology (namely $\beta_3 cov3G_{jt}$, $\beta_4 cov4G_{jt} * band4G_{jt}$ and $\beta_5 cov5G_{jt} * band5G_{jt}$). With the progress of mobile technology, the mobile broadband speed is progressively provided by 4G. With lower spectral efficiency, 3G

[5]The total market size is defined as the population multiplied by subscription penetration by country multiplied by 150%

[6]Our implicit assumption is that MNOs choose their prices on the retail market strategically, irrespective of the situation on the wholesale market and considering that MVNOs are followers.

provides better coverage than 4G/5G, ensuring primarily voice service. The first variable of quality is 3G coverage. Data services have been provided by 4G for the last ten years, and more recently by 5G. For this reason, the second variable of quality is the interaction between the 4G coverage and the 4G spectrum. It approximates the 4G network quality. The third variable of quality is the interaction between the 5G coverage and the 5G spectrum. This interaction approximates the recent 5G network quality. In other words, the term βq_{jt} must be understood as a measure of the maximum quality provided by operator j. This is different from the effective quality which can be affected by congestion effect.

The variables p_{jt} and $s_{j|gt}$ are endogenous and must be instrumented. We use as instruments the OPEX per user and BLP type instruments such as mean OPEX of competitors and/or mean ARPU of competitors (see Berry *et al.* (1995)). We consider that OPEX can hardly have a direct impact on market shares, except via prices.

From the demand estimation, the own- and cross-price elasticities can be calculated with the following expressions. The elasticity of demand for MNO j with respect to the price of MNO j is expressed as

$$\eta_{jj,t} = -\frac{\hat{\alpha}}{1-\hat{\sigma}} p_{jt}(1 - \hat{\sigma} s_{j|gt} - (1-\hat{\sigma}) s_{jt}) \tag{2}$$

This elasticity indicates also how the correlations among consumers' preferences are reflected in aggregate substitution patterns.

The cross-price elasticity of demand for MNO j with respect to a change in the price of MNO i is expressed as

$$\eta_{ji,t} = \frac{\hat{\alpha}}{1-\hat{\sigma}} p_{it}(1 - \hat{\sigma} s_{i|gt} - (1-\hat{\sigma}) s_{it}) \tag{3}$$

According to the nested logit structure, mobile offers in the same nest have a higher cross-price elasticity.

Total consumer surplus aggregates the net consumer valuation at time t by using the following expression

$$CS_t = \frac{N_t(1-s_{0t})}{\hat{\alpha}} ln(1 + (\Sigma_j^K exp(\frac{\hat{\delta}_{jt} + \hat{\beta}q - \hat{\alpha}p_{jt}}{1-\hat{\sigma}}))^{1-\hat{\sigma}}) \tag{4}$$

where K the total number of MNOs in the market. N_t is the market size at time t. $\hat{\delta}_{jt}$ corresponds to the fixed level of consumer valuation for a MNO.

3.2 Mobile operators' program

On the supply side, in the short run, assuming that the market is in equilibrium in each quarter, operators compete in prices given their mobile network coverage (3G/4G/5G) and associated spectrum. At equilibrium, prices and own-price demand elasticities $\eta_{jj,t}$ are related to marginal costs c_{jt} via the Lerner index.

$$\frac{p_{jt} - c_{jt}}{p_{jt}} = |\frac{1}{\eta_{jj,t}}| \tag{5}$$

By introducing Equation (2) into Equation (5), MNO's marginal costs can be recovered after the estimation of demand as:

$$c_{jt} = p_{jt} - \frac{1-\hat{\sigma}}{\hat{\alpha}(1-\hat{\sigma}s_{j|gt} - (1-\hat{\sigma})s_{jt})} \tag{6}$$

4 Main empirical results

We report the main results of the estimation of Equation (1) in Table 2. After presentation of the estimation results of the consumer demand, we then provide the average estimated own and cross-price elasticity of demand for each MNO, and finally the MNO's estimated marginal costs.

4.1 Demand estimation

Table 2: Main results of structural model of demand

VARIABLES	all MNOs' FE included ln(market share)	German MNO FE=0 ln(market share)
Price (-α)	-0.0551***	-0.0566***
	(0.003)	(0.003)
intra-MNO market share (σ)	0.6356***	0.6936***
	(0.047)	(0.041)
coverage3Gpop	0.9707***	1.0127***
	(0.111)	(0.109)
band4Gcov	0.0014***	0.0016***
	(0.000)	(0.000)
band5Gcov_2019Q3	-0.0104*	-0.0089
	(0.006)	(0.006)
band5Gcov_2019Q4	-0.0083	-0.0067
	(0.005)	(0.005)
band5Gcov_2020Q1	-0.0066*	-0.0053
	(0.004)	(0.004)
band5Gcov_2020Q2	-0.0062*	-0.0049
	(0.003)	(0.004)
band5Gcov_2020Q3	-0.0039	-0.0032
	(0.003)	(0.004)
band5Gcov_2020Q4	-0.0007	-0.0002
	(0.002)	(0.002)
band5Gcov_2021Q1	-0.0004	0.0001
	(0.002)	(0.002)
band5Gcov_2021Q2	-0.0015	-0.0008
	(0.003)	(0.002)
band5Gcov_2021Q3	0.0038*	0.0046**
	(0.002)	(0.002)
band5Gcov_2021Q4	0.0045**	**0.0052** **
	(0.002)	(0.002)
O2Germany	0.1604	No
	(0.148)	
TelekomGermany	0.2808*	No
	(0.153)	
VodafonGermany	0.2416	No
	(0.152)	
Other MNO fixed effect	Yes	Yes
time fixed effect	Yes	Yes
Observations	1,241	1,241
R-squared	0.903	0.903
First-Stage F-statistic	180.8	208.6

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

It is necessary to take into consideration the endogeneity problem that arises as a result of the simultaneous relationship between prices and market shares. Since the prices (ARPU) influence the quantity demanded and that the quantity demanded influences prices, the two variables are determined together. To overcome the endogeneity of price and within nest market share, we use two instruments: MNO's OPEX per user and average competitors' OPEX per user. All instruments lag the endogenous variables by one quarter. In the literature, it is usual to use characteristics of competing firms' products as instruments, which are referred to as BLP-type instruments. The first stage F-statistics, largely higher than the threshold of 10, indicates that the instruments are strong enough in terms of statistics.

Most parameters in Table 2 are precisely estimated, and the signs of parameter estimates are as expected. We present two estimations. The first one includes all MNOs' fixed effects. The coefficients for the dummies for the three German MNOs are not significant. As a result, we estimate a second model in which the fixed impact of German MNOs is assumed to be zero. The comparison of the two models indicates that the coefficients of all variables are similar. For this reason, for the sake of simplicity, the second estimated model is used to simulate our counterfactual scenarios.

The price coefficient ($-\hat{\alpha}$) is negative and significant in ways that are consistent with economic theory. The value of σ, statistically significant and between 0 and 1, shows that the nested structure is consistent. It shows that the differentiation among operators is relatively large.

Recall that network quality is the results of both the level of coverage and the availability in spectrum. The coefficient for 3G coverage is positive and significant. The ratio of coefficient of 3G coverage to the price coefficient ($\hat{\alpha}$) gives the consumers' willingness to pay (WTP) for a full population 3G coverage, around 17.6 Euros per month. Similarly, we could calculate the WTP for 1MHz of 4G which is equal to three cents per MHz per month. When we compare these WTP to mobile plan tariff, we notice that the WTP is greater than the associated component of mobile plan tariff.

The ratio of β_5 (the coefficient value (0.0052) of the variable band5Gcov2021Q4) to β_4 (the coefficient value (0.0016) of the variable band4Gcov) is similar to the ratio of 5G average spectral efficiency (4.8 Bits/Hz) to 4G average spectral efficiency (1.9 Bits/Hz[7]). The 5G requires three times less spectrum to provide the same network quality because β_5 is three times higher than β_4. This result is consistent with technological progress from 4G to 5G, i.e. the amount of data that can be transmitted over a given bandwidth grows with each successive generation.

[7] Average spectral efficiency value for different mobile technologies 3G/4G/5G from Coleago Consulting

4.2 Own and cross-price elasticities and marginal costs

The elasticities predicted by the model may be compared against elasticities obtained from the existing literature.

Based on the estimates of the demand model, own and cross-price elasticities are computed by using Equations 2 and 3. The marginal costs for each MNO are also computed following Equation 6. Figure 5 shows the own-price elasticities in Germany, which mostly vary between -1 to -4, depending on the MNO. As it can be seen, the absolute values of the own-price elasticities decrease over time. A lower absolute value of own-price elasticities of market demand suggests that customers become less sensitive to price fluctuations. This conclusion can be explained by the fact that mobile telecommunications services have become increasingly essential for customers over time. Mobile service has turned into a basic commodity that users cannot live without. Cross-price elasticities of demand for the three major mobile network operators (MNOs) are positive, but they are shrinking with time, indicating that customers are becoming less receptive to price changes. This observation is consistent with the trend seen for own-price elasticities, which may be found in the literature, See e.g. Sawadogo (2021)).

Figure 5: Own-price elasticities in Germany

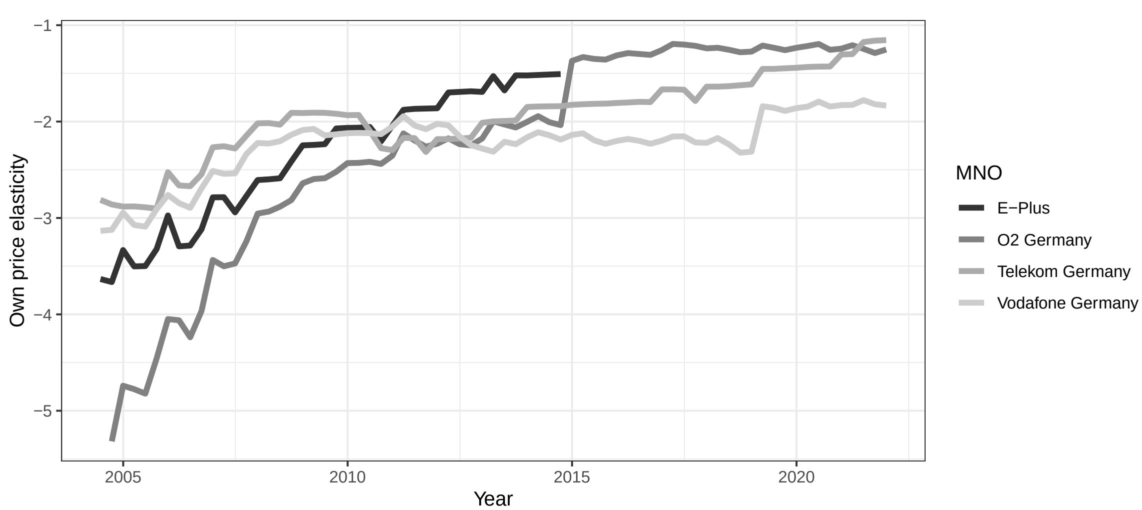


Figure 6: Cross-price elasticities in Germany

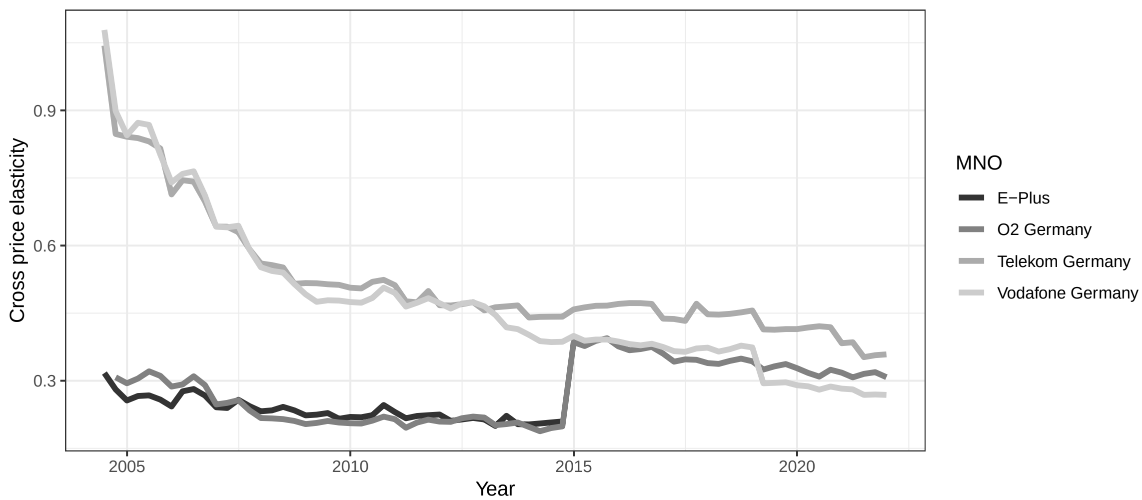
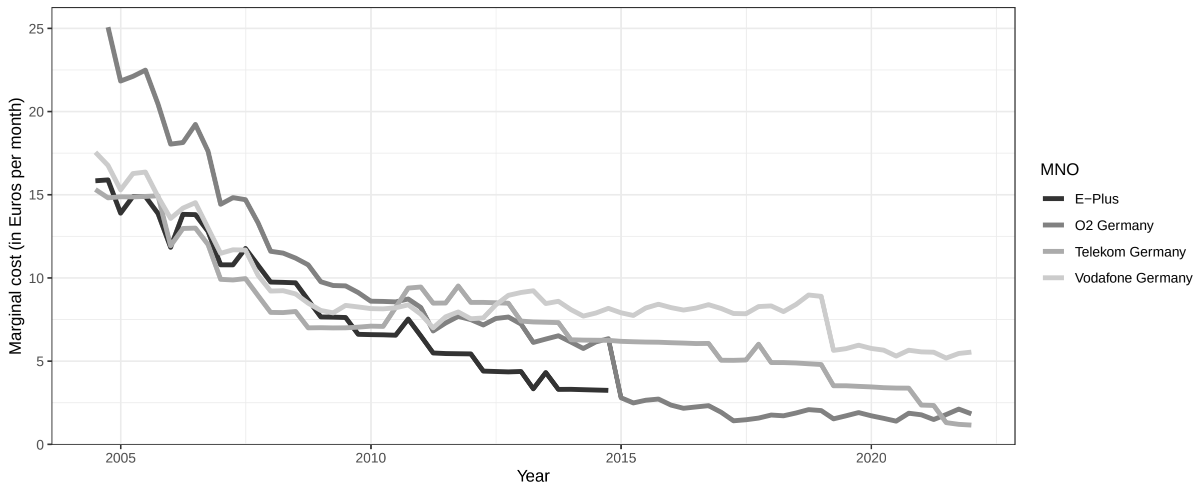


Figure 7 shows the estimated marginal costs per user for all German MNOs. Note that the marginal costs of all MNOs are decreasing over time. This decrease could be the result of ongoing investment by mobile operators to improve the quality of their mobile networks from one generation to the next.

Figure 7: MNO's marginal costs in Germany

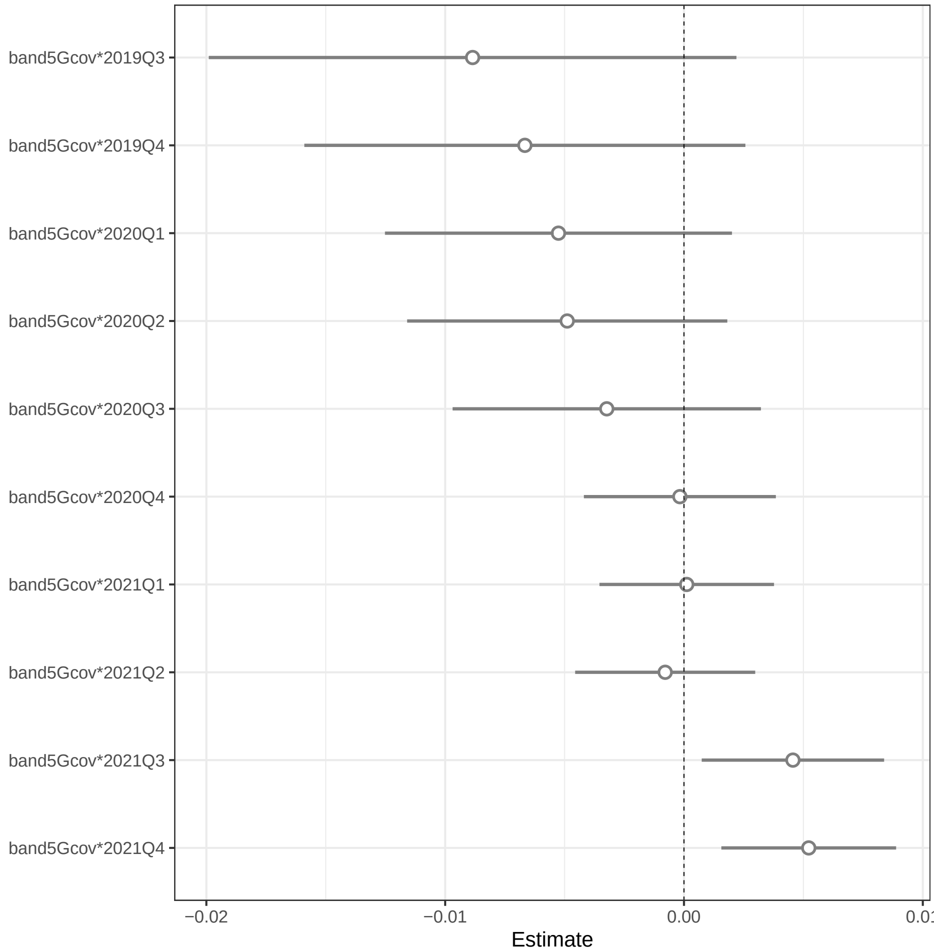


As seen in Figure 7, previous to the merger, E-plus had the lowest marginal costs in the market, while O2 had higher marginal costs. Following the merger, the marginal costs of operator from the merger (O2/E-Plus) continue to follow the E-Plus marginal costs curve. The marginal costs values are used below to simulate the Drillisch's entry as the fourth MNO in Germany.

4.3 Consumer's valuation for 5G network quality

We present here the consumer's valuation for 5G quality since 2019. We observe that consumers do not valuate 5G in 2019 and 2020, because 5G coverage was not yet sufficient and/or 5G compatible smartphones are not available and adopted by consumers. It is not surprising that it took three years for 5G coverage to be widespread and for 5G-enabled smartphones to be widely adopted. During 2019-2021, the expansion of 5G coverage and the adoption of 5G smartphones cause consumer valuation of 5G to become significant beginning in 2021Q3. Figure 8 shows that the 5G began to be positively and significantly valuated in the second semester of 2021. Because of this fact, the counterfactual simulations are computed with the 5G valuation at 2021Q4.

Figure 8: Consumer's valuation for 5G network quality



5 Simulating the impact of 5G spectrum allocation

There is an ongoing debate on how spectrum allocation could impact market structure and consumer surplus. We use the structural model to conduct counterfactual simulations to contribute to this debate. First, we simulate the impact of allocating the 50MHz of C-band to three existing German MNOs instead of allocating it to the fourth MNO. Second, we simulate the impact of assigning the 100MHz local assignment to the three current German MNOs or to the four

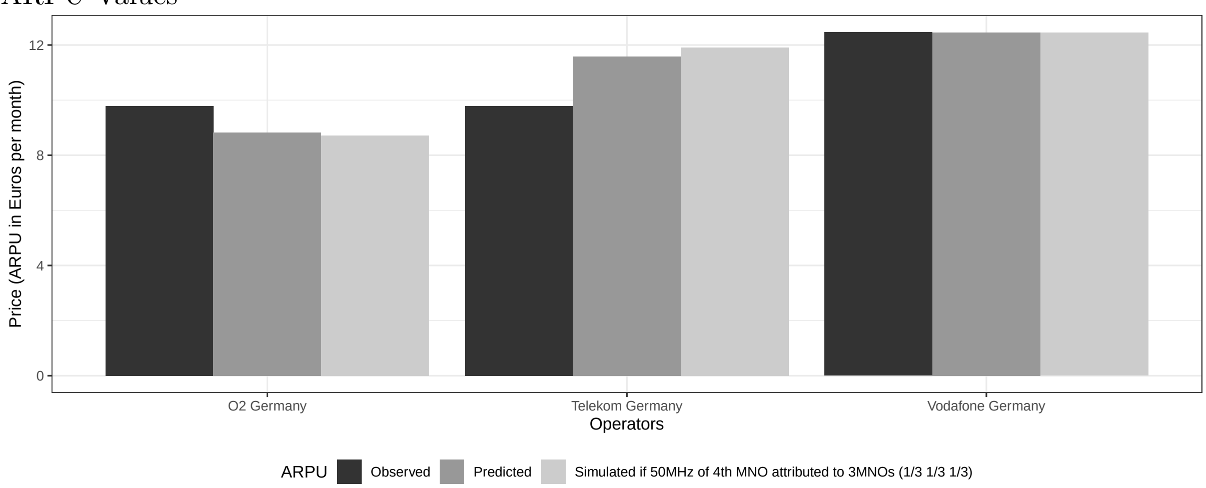
German MNOs (including the three incumbents and the new entrant, Drillisch).

In the different simulations below, it is important to notice that we do not pay attention to potential effects of changes in prices on quality and investment since the demand model above just considers the maximum quality provided by the operators.

5.1 Effects of the entry of the fourth MNO

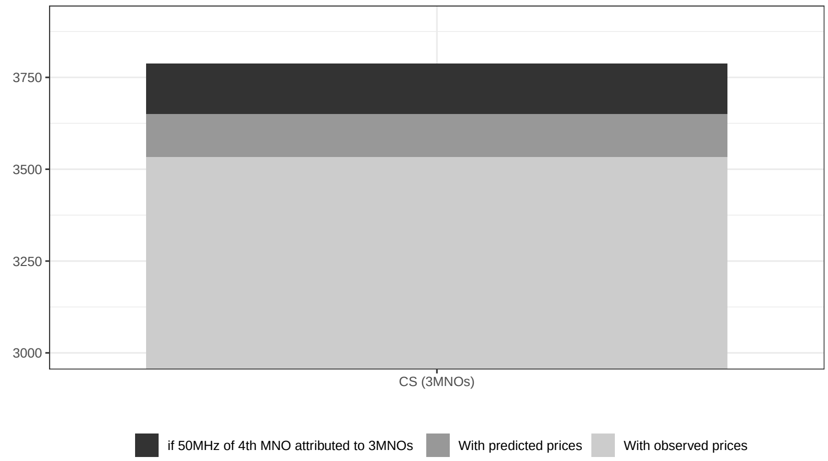
In this scenario, the 50MHz of C-band of the entrant MNO is allocated to the three incumbent German MNOs by dividing the frequency bands in three identical slots. We add the quantity of 50MHz divided by 3 in the term $\widetilde{band5G}$ to each of three existing German MNOs of equations in Appendix B. The numerical resolution of simultaneous equations in Appendix B provides the counterfactual values for prices $\tilde{p}_{jt}$, market share $\tilde{s}_{jt}$ and within-nest (intra-MNO) market share $\tilde{s}_{j|gt}$.

Figure 9: Comparison of prices in Germany at 2021Q4: Observed, Predicted and Simulated ARPU Values



Notes: The left bars of each MNO corresponds to observed ARPU in 2021Q4 for three German MNOs (O2 Germany, Telekom Germany and Vodafone Germany). The middle bars of each MNO correspond to model predicted ARPU. The right bars correspond to simulated ARPU by assuming 50MHz of C-band had been allocated to the three existing MNOs instead of allocating these 50MHz to the fourth German MNO.

Figure 10: Comparison of consumer surplus (in Millions €) change in Germany at 2021Q4 if 50MHz of C-band had been allocated to the three existing MNOs



We compute the consumer surplus of Germany at time t with equation 4. As shown in Figure 10, the gain in consumer surplus, linked to the hypothetical C-band spectrum allocation change, would be increased by 137 million Euros per month for the German mobile market. This is not a surprising result, given that unused 50MHz C-band spectrum had been used by three MNOs' consumers.

The simulation shows two messages. First, the consumer surplus would rise by 3.8% since the spectrum would have been used by consumers of the three existing MNOs to improve their network quality. While the fourth MNO has not yet deployed their 5G network, and their 50MHz was unused. Then, the change in price of the three MNOs remains negligible. One may argue that competition is not affected.

5.2 Consumer surplus change if reallocation of local assignment spectrum

In this section, We demonstrate how the consumer surplus would have changed if the 100MHz local assignment had been assigned to the three current MNOs or to the future four MNOs (including three existing German MNOs and the future fourth MNO). In the situation with three MNOs, we add 100MHz divided by 3 to $\widetilde{band5G}$ of three existing MNOs at 2021Q4. In the situation with four MNOs, we add 100MHz divided by 4 to $\widetilde{band5G}$ of four MNOs (3 existing MNOs and the future fourth MNO) at 2021Q4. We use three hypothesis to perform the simulation of four MNOs market situation. The first hypothesis is that the fixed effect is equal to zero for all four German MNOs. The second hypothesis is the marginal cost of the fourth MNO is equal to the lowest value of marginal costs among three existing MNOs (cf Figure 7). The third hypothesis is that the fourth MNO had a full coverage 5G.

In summary, the predicted and simulated consumer surplus are shown in the following table:

Table 3: Predicted and simulated Consumer surplus with different spectrum allocations

	3-MNOs market	4-MNOs market
spectrum before 2019 auction	3651	
50MHz more (Drillisch's spectrum)	3788 (+3.8% wrt 3651)	3669 (+0.5% wrt 3651)
100MHz more (Local assignment)	4069 (+11% wrt 3651)	3888 (+6.5% wrt 3651)

As shown in Table 3, in a three-MNOs market, the consumer surplus would increase by 3.8% if Drillisch's 50MHz had been attributed to the three existing MNOs. When 100MHz of local assignment is added, it would increase by 11%, through the same process. However, in a four-MNOs market with the same amount of overall spectrum, the consumer surplus would be lower than in a three-MNOs market.

Table 4: Observed and simulated Network quality with different spectrum allocations

	3-MNOs market	4-MNOs market
spectrum before 2019 auction	24.5	
50MHz more (Drillisch's spectrum)	25.2 (+2.9% wrt 24.5)	24.7 (+0.8% wrt 24.5)
100MHz more (Local assignment)	26.7 (+9% wrt 24.5)	25.7 (+4.9% wrt 24.5)

The changes in consumer surplus in Table 3 are closely related to the changes in network quality in Table 4. The network quality is formulated by the term βq in the equation 1 as a function of spectrum quantity in 3-MNOs and 4-MNOs markets. We observe that network quality rises as the total amount of spectrum increases. As the spectrum quantity is diluted from the 3-MNOs market to the 4-MNOs market, network quality may be higher in the 3-MNOs market[8].

Table 5: Predicted and Simulated Prices with different spectrum allocations

	3-MNOs market	4-MNOs market
spectrum before 2019 auction	11.1€	
50MHz more (Drillisch's spectrum)	11.3 (+2% wrt 11.1€)	11.0 (-1% wrt 11.1€)
100MHz more (Local assignment)	11.7 (+6% wrt 11.1€)	11.3 (+2% wrt 11.1€)

The increase in average price[9] in Table 5 is always lower than the increase in network quality in Table 4. As a result, any increase in price is always offset by an improvement in network quality. This is why the consumer surplus is increasing in two situations: first, when more 5G spectrum is assigned to each MNO; second, the consumer surplus is always higher in three-MNO market than in four-MNO market.

6 Conclusion and policy implications

This paper is aimed at evaluating the impact of conditions of spectrum allocation or reallocation in the determination of prices, quality and the market structure of the telecom sector. In a more concentrated market, the quantity of spectrum is less diluted, and operators can offer higher quality to their customers because the level of quality is directly function of the amount of spectrum available; In a more competitive market, where there are more operators, consumers can benefit from a lower price but at the expense of less spectrum for each operator, and so may be lower quality.

To address this trade-off, we first fit a nested logit demand model of mobile telecommunications services on a unique panel database for 23 MNOs of five major European countries from 2004Q3 to 2021Q4. Thanks to the richness of this dataset and its variability, we obtain reliable estimates, which allows to derive robust estimates of demand elasticities. The latter exhibit elastic demands and relatively high substitution among the services provided by the operators.

[8] The network quality in the Table 4 corresponds to the sum of the term βq over 3G/4G/5G and all MNOs of Germany at 2021Q4. The network quality of the fourth MNO is dependent on his 5G network coverage. The fourth MNO's 5G coverage is assumed to be 100% in the Table 4

[9] The average price in Germany is weighted based on the predicted or simulated intra-MNO market share at 2021Q4.

The own price elasticities are decreasing showing that the mobile telecommunications services are becoming more and more substitutable to other means of communications. The estimations also yield an adequate proxy of the mobile network quality for consumers by combining coverage data with spectrum data.

Assuming that operators compete in prices, we recover the estimated values of marginal costs which decrease over time, indicating that the telecom services are served in a more and more efficient way. Using this estimated demand model, we conduct a counterfactual simulations to measure the effect on consumer surplus of an incomplete spectrum allocation and the arrival of an additional operator in Germany. In the counterfactuals to these two spectrum allocations, we allocate, in the first case, the non-allocated spectrum to the operators already acting in the market or, in the second case, the spectrum previously allocated to a fourth operator to the three available operators in equal quantity. In both cases, the results show an increase in consumer surplus between 3 to 7 percent, mainly because, due a larger increase in quality compared to almost no change in prices. These simulation experiments illustrate the trade-off the regulator is facing when choosing a mechanism of spectrum allocation before competition takes places.

However this trade-off is cast in a static model. The question of dynamic efficiency is not addressed here as it requires a different framework. Indeed, what it is missing in our model is an analysis of interactions among the different mobile networks to understand the determination of quality at equilibrium. This is also required in view to discuss the optimal size of the industry. So the agenda for further research remains dense.

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Appendix

A Consumer's indirect utility

We start with the consumer's demand for mobile operators. It is assumed that there are $t = 1, ..., T$ observable markets consisting of $i = 1, ..., I_t$ consumers, facing j=1,...,J alternative MNOs in each country[10]. For each market, aggregated data are observed on MNO demand, prices (ARPU) and MNO's characteristics. Motivated by the fact that most individuals have subscribed to a mobile offer provided by a MNO in our sample, we use a nested logit model which groups consumers' choice into nests and creates a hierarchical structure. Individual i's indirect utility from subscribing MNO j at time t, u_{ijt}, is determined by the price and the observed mobile networks quality. The demand model is described by the following nested logit:

$$u_{ijt} = \beta q_{jt} - \alpha p_{jt} + \xi_j + \xi_{jt} + (1 - \sigma)\epsilon_{ijt} + \zeta_{igt} \tag{A-1}$$

where $\beta q_{jt} - \alpha p_{jt} + \xi_{jt}$ is the mean net value for choosing MNO j at time t that is common to all consumers. u_{ijt} depends on the quality of MNO's network quality q_{jt}, price of MNO j, a vector ξ_j with MNO-specific valuation and a vector ξ_{jt} of unobserved characteristics. The network quality q_{jt} includes both population coverage and associated spectrum. The term $(1-\sigma)\epsilon_{ijt} + \zeta_{igt}$ corresponds to the unobserved random errors and reflects consumers heterogeneity. ϵ_{ijt} is an individual-specific valuation for MNO j. The random variable ϵ_{ijt} is i.i.d. The nesting parameter σ measures the degree of preference correlation within a nest.

B Algorithm for counterfactual simulations

We compare two Nash equilibriums in the current situation and in a hypothetical situation where the spectrum allocation had been changed.

Firstly, demand having a nested logit structure, the system of equations to solve for the current situation for a given MNO j at time t is given by

[10] The number of markets in our study is the number of countries multiplied by the number of quarters. Markets are assumed to be independent and can be geographic (country), time series, or longitudinal

$$\tilde{c}_{jt} - \tilde{p}_{jt} + \frac{1-\hat{\sigma}}{\hat{\alpha}(1-\hat{\sigma}\tilde{s}_{j|gt} - (1-\hat{\sigma})\tilde{s}_{jt})} = 0 \quad \text{(A-2)}$$

$$\tilde{s}_{j|gt} - \frac{exp(\frac{\hat{\beta}\tilde{q}-\hat{\alpha}\tilde{p}_{jt}}{1-\hat{\sigma}})}{\Sigma_j^K exp(\frac{\hat{\beta}\tilde{q}-\hat{\alpha}\tilde{p}_{jt}}{1-\hat{\sigma}})} = 0 \quad \text{(A-3)}$$

$$\tilde{s}_{jt} - \tilde{s}_{j|gt}\frac{(\Sigma_j^K exp(\frac{\hat{\beta}\tilde{q}-\hat{\alpha}\tilde{p}_{jt}}{1-\hat{\sigma}}))^{(1-\hat{\sigma})}}{1+(\Sigma_j^K exp(\frac{\hat{\beta}\tilde{q}-\hat{\alpha}\tilde{p}_{jt}}{1-\hat{\sigma}}))^{(1-\hat{\sigma})}} = 0 \quad \text{(A-4)}$$

where $\hat{\beta}q = \hat{\beta}_3 cov3G_{jt} + \hat{\beta}_4 cov4G_{jt} * band4G_{jt} + \hat{\beta}_5 cov5G_{jt} * band5_{jt}$.

The marginal costs c_{jt} are calculated from equation (6) after the estimation of Table 2. c_{jt} are then introduced in the above system of equations. The numerical resolution of simultaneous equations (A-2), (A-3) and (A-4) gives predicted values for prices p_{jt}, market share s_{jt} and within-nest (intra-MNO) market share $s_{j|gt}$. We can measure the goodness of our structural model by comparing observed and predicted values of p_{jt}, s_{jt} and $s_{j|gt}$.To calculate consumer surplus in current situation, we introduce model predicted market shares and prices in expression of consumer surplus by equation 4.

By assuming that the network quality q could be changed by hypothetical spectrum allocation change, counterfactual market shares and prices are derived by solving the same system of simultaneous equations with $\hat{\beta}\tilde{q} = \hat{\beta}_3 cov3G_{jt} + \hat{\beta}_4 cov4G_{jt} * band4G_{jt} + \hat{\beta}_5 cov5G_{jt} * ba\tilde{n}d5_{jt}$, in which we change the value of $ba\tilde{n}d5_{jt}$ for German market. To calculate consumer surplus with hypothetical spectrum allocation change, we introduce counterfactual market shares and prices due to the spectrum change in expression of consumer surplus by equation 4. The consumer surplus change is the difference between the consumer surplus in counterfactual situation and the current situation predicted by the model of demand.

C Correlation test between mobile network quality (Ookla) and interaction term band*coverage

The average download speed experienced by mobile network users serves as a proxy for network quality. The download speed data is obtained from Ookla, a mobile internet data provider. Ookla hosts a platform that allows mobile network users to conduct speed tests. Users can test their mobile internet connection using a mobile browser or by installing the Ookla application on their phone. When a user performs a speed test, Ookla records the time and location of the test, the operator and technology used, as well as several metrics, including the average download/upload speed and latency.

We use linear regressions to determine the relationship between Ookla measurements for four Spanish MNOs from 2018 to 2020 (4G download/upload speed and latency) and our quality variable, which is the result of the interaction between 4G coverage and the associated spectrum. The table A-1 shows that the interaction term between 4G coverage and 4G spectrum band positively and significantly explains 4G download speed. These findings suggest that the interaction between network coverage and related spectrum is a good predictor of network quality.

Table A-1: Correlation test between network quality (download speed, upload speed and latency) measured by Ookla and interaction term 4Gband*4Gcoverage

VARIABLES	upload4G	download4G	latency4G
band4Gcov	78.403***	399.392***	-0.176***
	(10.037)	(50.472)	(0.036)
i.idMNO	y	y	y
i.YearMonth	y	y	y